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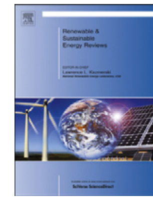

Solar radiation manipulations and their role in greenhouse claddings: Fresnel lenses, NIR- and UV-blocking materials

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ABSTRACT

From the global solar radiation which enters the greenhouse interior space only Photosynthetic Active Radiation (PAR) is absorbed by the plants and is important for their growth and photosynthesis. Thereby, sunlight spectral modifications which affect the quality and quantity of the incoming solar radiation are valuable and can be achieved by using specific kinds of cladding materials. In the present paper, some critical kinds of greenhouse claddings which are related with sunlight modifications are reviewed. The claddings considered include: Fresnel lenses, Near-infrared (NIR)- and Ultraviolet (UV)-blocking materials. The authors of the present article refer to some representative studies from the literature and make critical comments on each cladding category based on factors such as the feasibility for practical applications. Regarding the presented types of greenhouse covers, they have the potential for further development in a cost-effective way. Certainly, the penetration of renewable energy sources technologies is important and should be promoted. Towards this direction, cost-effective solar energy technologies, for example Fresnel lenses combined with simple Concentrating Thermal (CT) systems can provide advantages such as temperature/light control of greenhouse interior space along with production of thermal energy for greenhouse energy needs.

Contents

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1. Introduction

The global solar radiation which enters the interior space of a greenhouse can be divided into Ultraviolet (UV), Photosynthetic Active Radiation (PAR) and Near-Infrared (NIR). At this point it should be mentioned that UV radiation is divided into three bands: UV-a (320–400 nm), UV-b (280–320 nm), UV-c (100–280 nm) while PAR refers to wavelengths between 400 and 700 nm [1]. Moreover, visible spectral region is 400–780 nm [2]. In addition, infrared radiation covers the following ranges: NIR 780–3000 nm, Mid-Infrared (MIR) 3000–50,000 nm and Far-Infrared (FIR) $50{,}000-10^6$ nm [3]. From the above mentioned spectra only the PAR part of the incoming radiation is absorbed by the greenhouse plants and is important for their growth and photosynthesis. This means that specific manipulations of the radiation which enters the greenhouse interior space can offer advantages. In the frame of this concept, several claddings which cause spectral modifications of the sunlight have been reported in the literature. In the present paper three of these cladding types are critically reviewed: Fresnel lenses (FL), Near-infrared (NIR)- and Ultraviolet (UV)-blocking materials.

These specific types of covers may refer to materials which have the ability to separate beam from diffuse radiation such as FLs. Trapping the direct radiation is a way of achieving temperature and light control in greenhouse interior space. This is very important especially for countries with high solar radiation or during summer months. The direct part of the radiation can be collected and transformed into useful heat and electricity if the system includes Concentrating Photovoltaic/Thermal (CPVT). Thus, covering greenhouse energy needs can be achieved by integrating FLs on a part of the greenhouse south roof [4]. At this point it should be mentioned that passive systems which use only FLs integrated into the roof [5] are another possibility; however, these systems have several drawbacks and have not been studied extensively in the literature.

Another category is the NIR-reflecting materials. NIR is less absorbed by the plants while it is absorbed by e.g., greenhouse construction elements. Therefore, NIR leads to increase of greenhouse air temperature. Greenhouse heating caused by global radiation is desirable during cold months, but not during hot months because results in high air temperatures in greenhouse interior space and thus reduction of crop production [6]. In this way, by blocking NIR from entering greenhouse interior space, the quality and quantity of radiation entering the greenhouse can be altered. This spectral modification can be achieved by using specific cladding materials and may help to decrease the temperature of greenhouse interior space. Thus, heat load, especially long wave radiation which is emitted by the hot surfaces of the greenhouse, can be reduced and therefore the required cooling capacity. The NIR reflected radiation can be collected for example with a solar concentrator [7,8].

Another option is the UV-blocking covers. UV radiation can damage organic combination bonds and thus greenhouse cladding. The smaller wavelengths are more dangerous. In this way, several UV-stabilize additives are used during the construction of greenhouse plastic claddings. Most of the plastic covers which are used in greenhouses as well as glass covers are opaque to UV-b [6]. Several studies about UV-blocking claddings have been reported in the literature investigating how these materials affect plants, detrimental insects, fungi and bumblebees functions, red roses petal blackening. In general, UV-blocking covers seem to be promising and can be adopted in the frame of Integrated Pest Management (IPM) providing an environmental-friendly solution for pest and disease control.

In the present paper, three critical types of greenhouse claddings: FL, NIR- and UV-blocking materials which are related with sunlight modifications are reviewed. Moreover, the authors provide some critical comments on the presented coverings. In the paper which is an extension of the present study [9] more types of claddings (Fluorescent Solar Concentrators, Photoselective and other materials) which can modify solar radiation as well as some additional considerations such as claddings properties, future prospects etc, are presented. The innovation of the present work regards the critical review as well as the presentation of the greenhouse claddings which can modify solar radiation. Through this review the tendency of research during the last years is also revealed. On the other hand, the criticism of the authors of the present investigation provides a more complete picture regarding the presented technologies. Certainly, the penetration of new and promising systems is desirable but factors such as the practical applicability and the cost-effectiveness are important and should be taken into consideration. Conclusively, the development of greenhouses which are energy efficient as well as the penetration of renewable energy technologies such as FLs and other solar energy systems, are crucial and should be promoted.

2. Photosynthetically active radiation

The light which enters the greenhouse is an important factor and each greenhouse crop has specific light requirements. In terms of the greenhouse crops, most of them grow best at light wavelengths between 400 and 700 nm (PAR). Also sometimes, too much light can lead to stress [10]. Following are given some examples about the role of PAR for several crops.

Lettuce is sensitive to high light. Saturation occurs at 11 MJ/m^2 d while growth is inhibited at 19 MJ/m^{2}d. Moreover, uneven ripening tomato due to high light intensity can be eliminated by means of shading, although shading can reduce the overall yield. Fruit cracking/sun scald in tomatoes increases at high light, as indirect result of high fruit surface temperatures [10]. For the case of cucumber, Kläring et al. [11] conducted a study about the screening of cucumbers during leaf area development. Shading the plants during the first 5 weeks (under Central European winter conditions) resulted in reduction of the leaf area by 0.40% per 1% reduction in PAR. Potential leaf net photosynthesis decreased by 0.46% per 1% PAR reduction. On the other hand, Paradiso et al. [12], investigated the action spectrum of leaf photosynthesis and related leaf optical properties of reddish young leaves and green middle aged leaves of rose 'Akito' (grown in a heated greenhouse in Wageningen, The Netherlands, latitude 52°N). The green and reddish leaves showed similar total absorptance of 87% on average in the PAR range. However, the leaf absorptance of the green leaves, was around 550 nm lower than in the reddish leaves, but slightly higher at longer wavelengths.

Certainly the cladding material is an important factor which is related with the PAR that enters greenhouse interior space. First of all the type of the basic material of the cladding is associated with different PAR transmittances. For example glass, polycarbonate (twin wall), polyethylene (single layer) and acrylic claddings show PAR transmittances 90, 75, 88 and 86%, respectively [13]. Except of the basic material of the cladding there are also several specific characteristics of the covering material which influence the sunlight that enters into greenhouse interior space. In the present article, in the following section, FL, NIR- and UV-blocking materials as well as their role in sunlight modifications for greenhouses, are presented and critically reviewed.

3. Claddings and sunlight manipulations

3.1. Fresnel lenses

Fresnel lenses integrated into greenhouses, combined with concentrating systems, are a recent development in the field of

claddings. Following are given some representative studies from the literature.

3.1.1. Active systems

Linear FLs are lenses much thinner than conventional, produce a large focal area along the optical axis plane and provide an alternative solution for greenhouse cladding materials. The beam ray incidence angles (parallel and perpendicular to lens axis) as well as the concentration ratio profiles in the focal area of a linear FL, are illustrated in Fig. 1(a) and (b) [14,15], respectively. FLs can be integrated at the south roof of greenhouses and separate beam from diffuse radiation while can be combined with CPVT systems [16–18]. In Fig. 2(a), a FL greenhouse developed at the Wageningen University [19], is shown. In this figure the concentrators under the FL covers are also illustrated. Moreover, in Fig. 2(b) the geometry of a linear FL (left) and alternative absorbers (right) for water heating, air heating, PV (up) and hybrid PV/T-water, PV/T-air and PV/T-water plus glazing (down) are shown [20]. Lighting and temperature control can be achieved by placing the CPVs

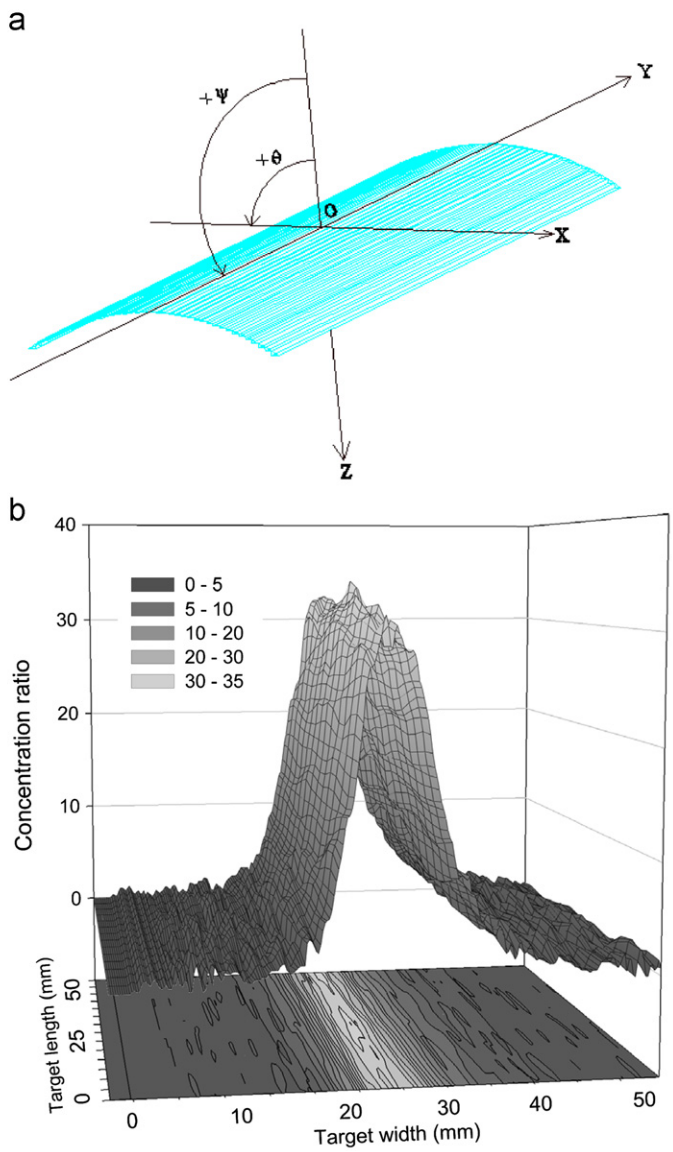

Fig. 1. (a) Linear Fresnel lens, (θ, ψ)=incidence angles. Beam ray is projected onto normal plane x and normal plane y: parallel (longitudinal angle ψ) and perpendicular (transverse angle θ) to lens axis [14], (b) Concentration ratio profiles in the focal area of a linear Fresnel lens [15].

(concentrators) at the focal point when solar radiation intensity is high and removing CPVs from the focal point when solar radiation intensity is low. In this way, light level in the greenhouse is optimized according to the cultivation. Solar tracking acts as illumination control depending on focusing all or part of the incoming radiation onto the absorber. FL–CPVT systems can produce heat and electricity for covering greenhouse energy needs such as ventilation, space cooling, space heating.

In the literature, there are only a few studies about FL greenhouses. The only theoretical study is the one of Chemisana et al. [4] and refers to a Computational Fluid Dynamics (CFD) analysis for the simulation of heat transfer and fluid flow phenomena in a FL–CPVT, single-span greenhouse, based on the k–ε turbulence model. Several configurations with FL combined with CPVT absorber pipes or without FL–CPVT, with or without ventilation openings, have been investigated in order to study the effect of FL and hot pipes presence and temperature. In Fig. 3 flow and temperature fields for a closed greenhouse, without and with FLs, are presented. In this figure the interaction of the flow with the temperature field is shown while for both cases the flow is thermally driven (no wind effect) and the buoyancy (stack) effect is predominant. The presence of pipes influences the temperature patterns and heat transfer in the greenhouse interior space; however, does not lead to significant increase of temperature mean value. In addition, the temperature at the gutter height is around 37 °C for the case without FLs while is around 34.2 °C for the case with FLs [4]. The overall results showed that depending on the greenhouse configuration (closed; ventilated) the pipes can influence to a lesser or higher extent temperature and flow fields in the interior space of the greenhouse and thus the plants. In general, FL–CPVT systems lead to better temperature and lighting conditions for plants growth which is very important especially during the summer months and for cultivations such as pot plants. At this point it should be mentioned that CFD is a useful tool for modeling greenhouses and several studies are available in the literature [21–24].

On the other hand, representative experimental studies are those of Jirka et al. [25] and Sonneveld et al. [19]. Jirka et al. [25] evaluated a greenhouse equipped with a glass raster of linear FLs (south-facing half of the roof) which concentrates the direct solar radiation in collectors while allowing diffuse light to pass. The greenhouse had been evaluated by measuring the distribution of incident solar energy into heat, and vegetable as well as fish biomass production. The results showed that for the climatic conditions of central Europe, the collector absorbs 12% of the total incoming global solar radiation, this energy is converted into heat 30–50 °C and the system consumes for heating approximately 50% less energy than a traditional one. Furthermore, the parallel production of vegetables and fish proved to be very successful since both processes complement and support each other and the system allows the efficient recycling of water and nutrients. Sonneveld et al. [19] developed and studied a FL–CPVT greenhouse with tracking. The results revealed that the removal of all direct radiation reduces the required cooling capacity during summer by a factor of approximately 4 while direct radiation is concentrated on a CPVT and converted to electricity and hot water (thermal yield 56%; electrical yield 11%; combined efficiency 67%). The collected thermal energy can be stored and used for winter heating while the generated electrical energy can be supplied to the grid and/or can be used for extra cooling with a pad and fan system and/or a desalination system. The results showed that the system is promising and the energy contribution is sufficient for the heating demand of well-isolated greenhouses located in north European countries. In addition, a recent study of Sonneveld et al. [26] includes information about the functions of a smart tracking system of a FL-greenhouse. Two motors bring

the receivers at the required positions. One motor controls the distance lens/receiver and the other controls the translocation of the receivers parallel to the lens. The positions of the focal line are within the bounds of the greenhouse construction for almost the whole year and only during winter, in the early morning and at the end of the day, the focal line is unreachable. Furthermore, another study of Sonneveld et al. [27] regards the electrical and thermal yield of a FL-greenhouse for Dutch climate. Measurements were performed with a Polymethylmethacrylate (PMMA) linear FL between double glass. Further improvement of the performance of the CPV-system can be achieved by using a polydimethylsiloxane (PDMS) lens directly laminated on glass and using AR (anti-reflective) coated glass. The best performance of the static linear FL was achieved with upwards orientation of the lens structures. In practice this is only possible by placing the FL between a double glass structure which keeps the lens clean and free of water. Finally, another recent study in the field of FL-greenhouses is that of Korecko et al. [28]. Active rasters were integrated into a greenhouse and the results did show reduction of the thermal load in greenhouse interior space with parallel production of hot water.

At this point it should be noted that there is dependence between FL systems and parameters such as the location and the tilt angle. Chemisana et al. [29] investigated a configuration based on a static linear FL and a moving absorber (this configuration has building integration advantages) in order to examine this dependence. A combined PVT collector was studied and the optimal tilt angle of the system for the climatic conditions of Barcelona was determined. The results revealed that by adopting the optimum tilt angle for the inclination of the system, the annual production (thermal and electrical energy) is increased. The proposed methodology can be utilized for the case of the buildings (general) and certainly for the case of FL-greenhouses, since greenhouses can be considered as a specific type of buildings and thus building integration requirements should be fulfilled.

Finally, it should be mentioned that another interesting application of FLs refers to microalgae cultivation. Masojídek et al. [30] studied a novel two-stage experimental photobioreactor based on linear FLs which transmitted diffuse light and concentrated the direct component of solar radiation on the surface of the glass cultivation tubes placed on a movable frame. The culture of the green microalgae *Haematococcus pluvialis* was first grown in low-irradiance units, and then exposed to supra-high irradiance. The results did show that the rate of astaxanthin production was 30–50% higher than in the culture exposed to 'ambient' irradiance, revealing the advantages of the proposed system.

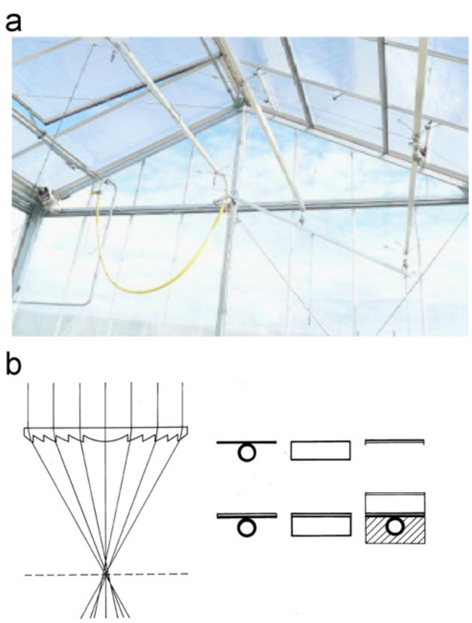

Fig. 2. (a) Fresnel lenses (FL) integrated into the south roof of a greenhouse (the concentrators at the greenhouse interior space, below FLs, are also illustrated) [19], (b) the geometry of a linear FL (left) and alternative absorbers (right) for water heating, air heating, PV (up) and hybrid PV/T-water, PV/T-air and PV/T-water plus glazing (down) [20].

3.1.2. Passive systems

The use of a simple, passive system is an alternative solution instead of using the above mentioned active ones. Following is given a representative study from the literature. Kurata [5] conducted a work about the effects of applying a FL to a south roof of an EW-oriented single-span greenhouse by using scale

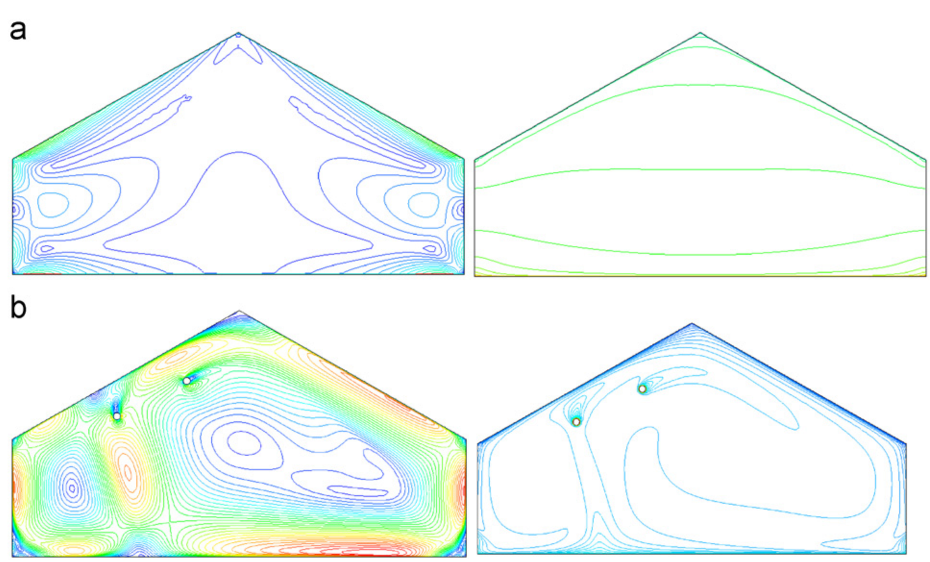

Fig. 3. Flow field (air velocity, m/s) (left) and temperature contours (°C) (right) for closed (with no ventilation openings) greenhouse configurations: (a) without Fresnel lens—CPVT, (b) with Fresnel lenses and 2 pipes (50 °C). External air velocity=2.2 m/s. Flow range: (a) $0-2.59\times10^{-2}$, (b) $0-2.97\times10^{-1}$ m/s. Temperature range: (a) 30.25 – 45, (b) 28.82 – 50.15 °C. Temperature at the gutter height (approximately): (a) 37, (b) 34.2 °C [4]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

models and artificial light as well as under natural light conditions. The experiments confirmed the theoretical predictions that the application of a Fresnel prism increases light transmissivity in winter while decreases it in summer. Two functions of a prism were relevant for this study: refraction and total reflection because the first is related with the high transmissivity of a greenhouse in winter while the second reduces the transmissivity in summer. This shift occurs due to the seasonal change of the sun position. Finally, it should be mentioned that the experiments also revealed large spatial variations of the light transmissivity in the greenhouse.

3.1.3. Critical issues

Certainly, the integration of FL into greenhouses is an interesting and promising application; however, there are some crucial factors which must be taken into consideration. For example the use of 2-axis tracking for FL-greenhouses, has several disadvantages such as increased cost, necessity for more accurate electronic control and greater mechanical loads. Therefore, a concentrator which could be combined with 1-axis tracking is an alternative solution for the reduction of the cost and mechanical requirements.

At this point, it should be mentioned that although the passive systems are simpler and much cheaper, their efficiencies certainly are not the same with the efficiencies of the active ones. In the literature, the only recent study about this type of passive systems for greenhouses is that of Korecko et al. [28]. Passive rasters integrated into a greenhouse were investigated and the results showed that the rasters reflect the direct component of solar radiation back to the exterior; thus, the interior heat load of the greenhouse is reduced. Probably the reason for which this type of systems has not been studied extensively in the literature is related with the low efficiencies of these passive devices. General, in order to compensate the cost and the efficiency, the use of FL combined with simple Concentrating Thermal (CT) and with 1-axis tracking; for light/temperature control and production of heat; seems to be an attractive and cost-effective solution for the case of the integration of FLs into greenhouses.

3.2. NIR-blocking

Another category of claddings are the NIR-reflecting materials. Since NIR is less absorbed by the plants while it is absorbed by the construction elements of the greenhouse, leads to the increase of greenhouse air temperature. For this case, NIR-blocking claddings can provide advantages by reducing the cooling needs of a greenhouse. In the literature there are several studies and refer to different types of technologies: solar concentrating systems, fluid roofs etc. In the following (Sections 3.2.1 and 3.2.2), these claddings are presented.

3.2.1. Several technologies

A NIR reflecting greenhouse coating (with high PAR transmission) along with a solar driven cooling system was developed and studied by Sonneveld et al. [31–33,7,8]. Two applicable film materials with multilayer coatings, one metallic and one dielectric, were found to have useful transmission and reflection properties. In Fig. 4 the spectral transmission and reflection properties of these films (for perpendicular incidence) are illustrated. The metallic multilayer film did show good reflection for almost the whole range of NIR between 900 and 2500 nm [7]. Regarding the collection of the reflected energy, when the NIR reflecting coating is designed as a parabolic or circular shaped reflector integrated into the greenhouse, the reflected solar energy can be received by a CPV (cooled with air or water) at the focus and thus the system can deliver sufficient electric energy to drive a fan and pad cooling system. The excess energy can be used for desalination and/or energy supply [31]. An electrical peak power of approximately 30 W/m^2 and a thermal peak power 121 W/m^2 are expected with 900 W/m^2 illumination. Under Dutch climatic conditions the yearly produced electrical energy by the prototype is 20 kW h/m^2 while the yearly thermal yield is 161 kW h/m^2. The concept was found to be feasible with existing materials and components; however, the prototype performance is limited by the small spectral range (800–1200 nm) of the applied NIR reflecting material. Also improvements are required for the focusing unit. With improved NIR reflectance, an increased performance of the system could be expected [8]. In Fig. 5, the concept of a NIR-blocking greenhouse with a spectral selective cylindrical mirror and a collector in the focal line is illustrated [7].

The study of Sonneveld et al. [7] refers to the feasibility of the above mentioned system. Several configurations for the PVs such

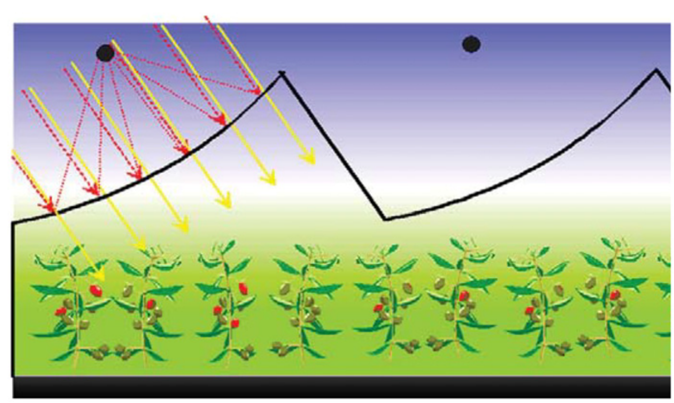

Fig. 5. Greenhouse with spectral selective cylindrical mirror and the collector at the focal point (red and yellow lines indicate NIR and visual light, respectively) [7]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

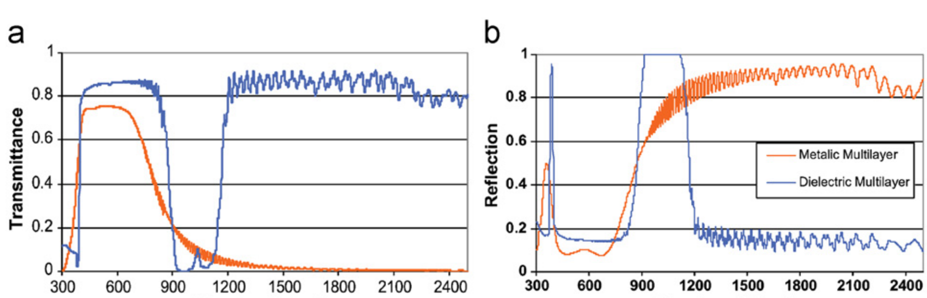

Fig. 4. (a) Transmittance and (b) reflectance of the spectral selective reflecting metallic and the dielectric multilayer film [7]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

as CT vs. CPV and CPVT, different materials for the PV cells (Ge, GaSb, CIS, Si) and different options of the transformation of the NIR radiation to electric energy by thermal systems, were studied. For the option with thermal conversion driven electric generator, the typical yearly yield was 32.5 kW h/m^2 and despite of this higher yield the Si PV was preferred because the thermal conversion system required much higher investments. According to Sonneveld et al. [7], in terms of economic evaluation of the PV, PVT and thermal conversion, the concentration factor has a large influence on the investment costs but increasing this factor results in high costs for the concentrating system. Furthermore, the results showed that PV conversion is economically more attractive than the "only thermal conversion" option and Si cells are the most economically attractive cells for this type of system.

On the other hand, López-Marín et al. [34] conducted a study about cool plastic films for greenhouse covering in Southern Spain. The farmers that grow peppers in Murcia, Southern Spain, have problems during summer months because of the high temperatures in the interior space of the greenhouse. In the above mentioned work an experimental plastic film with NIR-reflecting pigments (NIR-blocking cover) was evaluated. The results revealed that the lower temperatures lead to greater yield and better fruit quality.

Another recent study about the NIR effect on greenhouse climate for various climatic conditions, including Spain, was conducted by Kempkes and Hemming [35]. Model calculations of the effect of different NIR-absorbing prototype plastic films on the greenhouse climate for the climatic conditions of Southern Spain were presented. The effect on greenhouse air temperature/humidity and crop transpiration was analyzed.

On the other hand, Hemming et al. [36] investigated the optical properties of available NIR-filtering materials. The study included a calculation method to quantify the energy reduction under these materials and thus the contribution in greenhouse cooling. The materials were characterized by the transmission, reflection and absorption. Most of the tested materials had a suitable PAR transmission of 90% and higher. The advantage of the NIR-filtering coating on glass is that the heat is kept out of the greenhouse by reflection while NIR-filtering pigments used in PE films are less effective and lead to a substantial decrease in PAR transmission. The results for polyethylene terephthalate (PET) films with NIR-reflecting coatings were similar to those for the glasses; the PAR transmission was still high and the NIR reflection could be optimized. White washes were also investigated and did show reduced PAR transmission depending on their concentration. The results of the study revealed that the best NIR-filtering material has not still been found and NIR-reflecting materials are more efficient than NIR-absorbing materials. Furthermore, wavelengths from 800 to 1100 nm rather than 1100–2500 nm should be reflected out of the greenhouse and NIR-filtering is not desirable during winter-time. In addition, NIR-filtering plastic film materials are able to reduce the amount of NIR energy by up to 25%, NIR-filtering glasses are able to reduce NIR by 50–70%. In terms of the cultivation, crop transpiration is significantly affected by NIR-filtering measures. Plants need to maintain high transpiration rates during hot periods in order to cool themselves. The transpiration rate can be about 30% lower under a 100% NIR-filtering greenhouse cover during the summer months while a 50% NIR-filtering cover still reduces transpiration rate by 10–15%. Finally, NIR-filtering (moveable) screens could be an alternative solution in the future.

Mutwiwa et al. [37] studied the effect of different greenhouse cooling technologies (natural ventilation, evaporative cooling and spectral modification) on the greenhouse microclimate and on the plant physiological processes. The study included the use of NIR reflecting pigments which decrease air temperature but alter the spectral transmission of the greenhouse cover. The effect on the growth of tomato plants (*Lycopersicon esculentum* (Miller) 'FMTT260') was studied by online measurement of plant response (phytomonitoring), in greenhouses located at the Asian Institute of Technology (Bangkok, Thailand). The results showed clear differences in the way that plants responded to different greenhouse microclimates. During the warm season, the NIR reflecting pigment significantly reduced air temperature, leaf transpiration and net photosynthesis inside the greenhouse; however, the differences were small during the cool season. The fan/pad cooling system reduced both transpiration and temperature (air and leaf) but had minimal effect on net photosynthesis over the cool season. The use of NIR reflecting pigment has the advantage of reducing the heat load though it leads to some loss of PAR and is complex to apply uniformly on greenhouses with plastic roof covers. During the cool season (especially when wind speeds are low), the porosity of insect screens had little effect on greenhouse microclimate and plant growth. Evaporative cooling is effective in temperature reduction but increases the humidity inside the greenhouse, thus subjecting the plants to fungal attacks. The combination of NIR reflecting pigments and insect proof screens (natural ventilation) could be incorporated in protected cultivation in the tropics.

The approach of Daponte [38] for optimization of spectral transmission of greenhouse covers by using interference within thin layers, was confirmed in a field test in the frame of Von Elsner investigation [39]. During a summer experiment, two different types of pigments in two concentrations were compared with conventional white wash on experimental plastic film greenhouses. In the above mentioned study the method of spectral weighing of transmission curves by standardized solar spectrum and plants absorption factor delivered results on radiation quality. This seems to be a promising technique for all investigations related to photoselective greenhouse covers, mainly those of plastic. The results clearly showed that the inside temperature dependents on the overall reduction of the global radiation. Both interference pigments reached higher PAR levels than conventional shading and further benefit is obtained with the "870" pigment because it allows more morphologically effective radiation transmission. Pigment interference is effective and this means less transmittance in the NIR range. Furthermore, heat load at absorbing surfaces in the greenhouse is reduced but this does not affect leaf surfaces because their NIR-absorption factor is low. Non-plant surfaces will absorb less and will thus heat the air less while the actual extent in air temperature depends on plant mass in the greenhouse and possible ventilation and cooling rates.

On the other hand, Blanchard and Runkle [40], studied the influence of NIR-reflecting shading paint on greenhouse environment, plant temperature, growth and flowering of bedding plants. A glass-glazed greenhouse (lat. 42.7°N) with a commercially available NIR-reflecting (NIR-R) or neutral (N) shading paint was investigated. During two summer seasons, shading paints were applied to the glazing exterior of different greenhouses. It should be mentioned that the mean daily transmission of PAR was similar. Poinsettia (*Euphorbia pulcherrima* Willd. ex Klotz) or bedding plants were grown inside each greenhouse. The NIR-R paint transmitted 67, 8, 24, 30 and 29% less UV-a, red, far-red, NIR and SWR (Short Wave Radiation), respectively, than the N paint. Transmission of blue and green light was 4.7 and 4.5% greater, respectively, under the NIR-R in comparison with the case under the N paint. Furthermore, the ratio of transmitted PAR per unit of SWR under the N and NIR-R paints was 1.8 and 2.6 μmol/W s, respectively. In terms of the temperature, during day, mean greenhouse air, shoot-tip, and leaf temperatures were 0.4 °C to 1.5 °C, 0.4 °C to 1.2 °C and 0.7 °C to 1.5 °C higher, respectively, under the N paint compared with the case under the NIR-R paint.

Verlodt and Verschaeren [41] tested a new interference film which is a photoselective film developed with the purpose of reducing the extreme temperatures occurring in the greenhouses of the climates with hot summers. This film contains a new type of pearlescent pigment in order to reflect solar heat (NIR) in combination with an improved light transmission (PAR). The new film had been tested amongst others in the South of Tunisia (winter and spring 1997) for a tomato crop growth under classical tunnels. The results showed that during hot days the new film reduces the maximum temperatures by 1–2 °C and in general moderates the extreme temperatures, so that the climate is more favorable for the crop.

García-Alonso et al. [42] studied a new generation of cool plastic films which block a part of the NIR radiation. The films were tested in Spain, Colombia, Mexico and the Dominican Republic and might reduce maximum diurnal temperatures inside the greenhouse at a relatively low cost. The first field trial was conducted in Southern Spain and referred to pepper crop. The results showed that by using the new cool film, the height of the plants, their vegetative development and their commercial yield were higher while the number of waste fruits was lower compared to a standard reference film.

In Wageningen UR the potential of several NIR-filtering methods for possible applications in Dutch horticulture was investigated [43]. NIR-filtering can be achieved by the cover of the greenhouse or by internal or external moveable screens. The objectives of the above mentioned study was: to quantify the effect of different NIR-filtering methods on greenhouse climate, energy saving, growth and production of tomato; to estimate the amount of NIR which should be blocked in order to get positive effects under Dutch climate conditions. The research revealed that there are technical/economical potentials for filtering NIR by the greenhouse covering or by using a moveable screen which does not limit ventilation. In terms of tomato cultivation, the production can be potentially increased by 8–12% depending on the NIR-filtering material used. A greenhouse covering material, which is assumed to filter out all incoming NIR can increase tomato production. This can be attributed to factors such as: lower temperature in greenhouse interior space (during summer 1–2 °C lower than in a reference greenhouse); lower crop temperature (during summer 0.8–2 °C lower); the ventilation openings can be kept closed for a longer time and this means higher CO_2 concentrations in the greenhouse; lower crop transpiration during summer months. These parameters result in an increased daily dry matter production, especially from the end of March until the end of September. More specifically, based on the results of ref. [43], tomato production did show an increase of 8.6% during summer. On the other hand, a covering material which reflects only 50% of the NIR was less effective, since greenhouse climate effects are smaller than those described above. For this case (more realistic) the production increase was about 4.9% during summer months. On the other hand, another option which may lead to 10–12% increase of tomato production is the use of a NIR-filtering coating on glass in addition to an anti-reflection coating. In this way, PAR-transmission can be increased to 95% and almost 100% NIR-filtering can be achieved. Furthermore, for this case factors such as the availability and the cost of these materials should be taken into consideration. However, greenhouse climate calculations have shown that a NIR-filtering internal, horizontal screen has no advantages since air temperature in the greenhouse increases about 1–2°C during summer months and can reach even higher values upto 5–6°C during clear summer days at noon. In addition, the closed screen limits the air exchange with outside, the NIR-filtering effect of the screen is notable to compensate this limitation and the radiation energy in the PAR region is still enough to increase inside air temperature. Furthermore, crop production is not increased by the use of an internal screen while bud abortion and reduced fruit set are observed. Thus it is preferable the use of screens which do not limit free air flows e.g., an external moveable screen. An external screen can decrease greenhouse air temperature about 2°C during hot summer days while decreasing crop temperature and increasing CO_2 concentration. The right screen strategy is important as well as the optical properties of the film. A screen which reflects only 50% of the NIR has less effect than a screen which reflects100%. A screen, which is closed more often, has more effect than a screen that is closed at higher outside radiation levels. Furthermore, the film should have very high PAR-transmission (at least 90%, better 95%), since screens always create a second light-intercepting layer in the greenhouse and decrease PAR. Such NIR-filtering screens can increase tomato production by 2–8% depending on the optical properties and screen strategy. Conclusively, the different NIR-filtering methods (greenhouse covering, moveable screens) influence greenhouse climate parameters and crop parameters. The overall analysis (greenhouse climate, crop growth, production parameters) did show that there are advantages and economical potentials to reduce air temperature of greenhouse interior space during summer (and thus cooling capacity) and increase tomato production by reflecting NIR by means of the greenhouse covering or by using a NIR-reflecting screen, which does not limit greenhouse ventilation in Dutch horticulture [43].

Finally, it should be noted that Kempkes et al. [44] conducted a study about a rose crop glasshouse experiment with an internal movable, NIR-reflecting screen. The effects on greenhouse temperature, carbon dioxide management, humidity and crop transpiration, were analyzed. Moreover, film prototypes which selectively reflect NIR have also been developed and tested for the climatic conditions of Indonesia [45]. Finally, it should be noted that film prototypes which selectively reflect NIR have also been developed and tested for the climatic conditions of Indonesia [45].

3.2.2. Fluid roofs

Control of NIR radiation which enters greenhouse interior space can be also achieved by means of fluid roofs. Following are given some examples from the literature.

Feuermann et al. [46] evaluated a new liquid radiation filter (LRF) in desert environment. The new LRF was based on a water soluble, antioxidation stabilized, iron salt. At the concentration used, the iron based LRF transmitted more of the PAR than the copper based LRF. In addition, the iron-based filter was more effective in absorbing the NIR part of the radiation. The net absorbed heat by the LRF was transported by the circulation of the fluid to a heat exchanger. There, the heat was exchanged with water which was circulating between the heat exchanger and a water tank. The LRF leaded to"thermal blanket effect". At night, the LRF and the water pumps continued to operate and thus greenhouse cladding was the energy sink. Transfer of energy took place from the water tank to the LRF which entered the cladding at a relatively high temperature. LRF temperature decreased while it flowed through the greenhouse cladding, mainly due to heat losses by long wave radiation to the sky and by convection to the ambient and greenhouse air. At ambient air and sky temperatures lower than the greenhouse air temperature, the LRF typically resulted in greenhouse cladding temperature somewhat lower than that of the greenhouse air. However, the average temperature of the entire greenhouse envelope was generally warmer than it would have been without the LRF circulation. In this way, LRF acted as a thermal blanket, ensured leaf temperature higher than greenhouse air dewpoint temperature throughout the night,

precluding condensation on the leaves and therefore germination and spread of pathogenic fungal spores. On the other hand, during summer, the LRF removed a significant fraction of the heat during daytime, so the greenhouse could be closed approximately 7 to 10 out of the 14 h of daylight, enabling effective CO_2 fertilization and thus increased growth rates.

In addition, Feuermann et al. [47] developed a computer simulation model to study the relationship between design parameters of a LRF greenhouse and its thermal performance under different climatic conditions. The greenhouse had a selectively absorbing LRF circulating in a double layered cladding. The filter removed much of the NIR of solar radiation while transmitting most of the PAR and thus resulted in great reduction of the heat input to the greenhouse and better temperature control. Validation of the model was performed with data from a 330 m^2 LRF greenhouse, operating in the Negev (Israel) desert highlands. The predicted greenhouse temperatures did show agreement with the measured values within 1–2 °C. Performances for a LRF as well as for a conventional greenhouse were compared using the simulation and hourly meteorological data for central Israel. For the summer (May–October) the number of daylight hours during which the LRF greenhouse could remain closed was larger by about two-thirds than that of the conventional greenhouse. This is very crucial for the case of CO_2 fertilization because the greenhouse should be closed during daylight hours.

Gale et al. [48] conducted a study about engineering and economics of liquid radiation filter greenhouses (LRFG) (Fig. 6). LRF is transparent in PAR and absorbs NIR as well as longer wavelengths and together with the polycarbonate cladding absorbs most of the incident UV. LRF acts as a selective solar collector and as heat transfer medium with the heat in winter being stored in a water storage tank. During summer excess heat is dumped to the environment and for the case of heat storage, heat could be released back to the greenhouse at night, reducing the cost for winter heating. LRFG has been perceived as an expensive alternative to conventional greenhouses. However, due to the fact that these filters can control the greenhouse climate, extensive fertilization with CO_2 is possible. This means significant yield increase. An economic analysis, which took into account actual costs and expenditures for the commercial LRFG, revealed that the additional cost per unit area of the LRFG is only about 35%, if put in the perspective of an entire greenhouse farm, including infrastructure. This amount could be smaller if the cost of land was also included. For example in Israel it was found that only a 15% increase in production of a *Ficus* sp. rooting nursery would be sufficient to equalize profitability. In general, attention must be paid for the choice of crops to be growth in LRFGs as only those species that could benefit from a large increase in CO_2 fertilization can lead to economically satisfactory results.

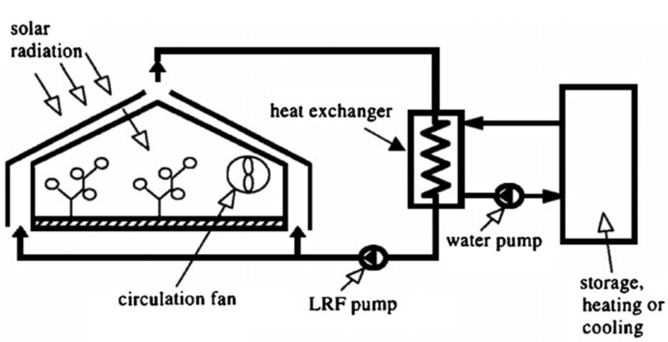

Fig. 6. Schematic of a Liquid Radiation Filter Greenhouse (LRFG). LRF is transparent in PAR and absorbs NIR and longer wavelengths [48].

3.2.3. Critical issues

It can be concluded that the field of NIR-blocking claddings includes several and different categories such as solar concentrators, PE films, fluid roofs etc. Certainly, the cooling effect of the NIR-blocking covers is a solution for areas with strong sunlight and hot weather as well as for the case of nurseries and shade-loving plants. Nevertheless, when selecting a cladding for a specific application several different factors must be taken into consideration such as the cost and the reduction of PAR. Furthermore, for the case of systems such as solar concentrators which are installed in the roof of the greenhouse, the extent at which these systems are feasible from practical point of view should be addressed. Aspects such as the durability in adverse weather conditions, wind durability, aesthetics, cost as well as the architectural integrability must be taken into consideration.

Following are given some additional considerations [49] which should be addressed for the case of NIR-blocking covers: although fluid-roof claddings prevent a considerable amount of heat from entering the interior space of the greenhouse, their PAR transmission is relatively low because of their complex structure; NIR-reflecting plastic films seem to be the most suitable, low cost and simple claddings for greenhouses under arid conditions; NIR-reflecting materials are more efficient than NIR-absorbing materials (for example NIR-absorbing pigments used in PE films decreased PAR transmittance more than the NIR-reflecting pigments); in mild climates NIR-filtering is not desirable during winter and NIR-filtering claddings should not be used in heated greenhouses in Northern countries because they cause undesirable temperature drop; NIR-filtering movable screens should be used for shading outside the greenhouse cover in order to avoid affecting greenhouse ventilation.

3.3. UV-blocking

UV-blocking covers affect not only plants growth but also detrimental insects, fungus and bumblebees. Complete or partial absorption of solar UV radiation by greenhouse cover, interrupts the life cycle of several fungal pathogens and alters the visual behavior of many insects [50]. This type of claddings has been studied for several climatic conditions e.g., for the case of Spain [51], Indonesia [45] etc. Following are given some representative studies from the literature, divided into five categories.

3.3.1. UV-blocking and plants growth

The use of UV-blocking greenhouse cladding materials is spreading out in protected cultivation and their effects on pest and disease management have received much attention. However, there are only a few studies about these radiation manipulation effects on crops.

A representative study is that of Kittas et al. [52] and refers to the effect of two UV-absorbing greenhouse-covering films on growth and yield of an eggplant soilless crop. This study aimed at assessing the effects of UV absorbing film on the behavior and production of an eggplant crop. Two different UV absorbing films (0 and 3% UV transmittance) and a standard polyethylene (PE) film (5% UV transmittance) were compared. The findings revealed that the eggplants grown in the greenhouse with 0% transmission to UV light were about 21% taller and had about 17% higher leaf product (leaf Length × Width product: LW) than the plants grown in the greenhouse with 5% transmission to UV light. In Fig. 7 the evolution of the LW product (bars refer to the average over eight plants and the dotted line indicates the de-leafing). The results revealed that the final mean LW per plant was 1.42, 1.77 and 1.66 m^2, for the UV5%, UV3% and UV0% greenhouses, respectively. Since the production was slightly increased in quantity (20%) and

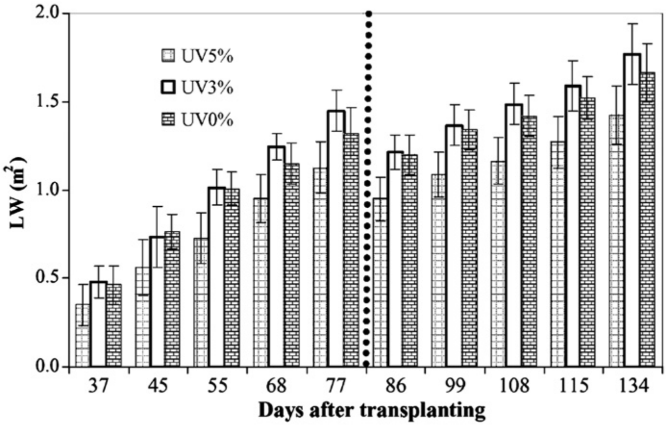

Fig. 7. The effect of a UV-absorbing cover material on the evolution of the leaf Length Width product (LW) per eggplant in three greenhouses [52].

quality (bigger fruits) in the greenhouse with absence of UV light compared to that with 5% transmission coefficient, it can be concluded that growing soilless eggplant under UV-absorbing material can be achieved with the same or better results as under standard covering material. Furthermore, any other enhancement that the UV-absorbing film can have (lower pest and disease impact on the crop, lower pesticide load and costs) will be an additional benefit for the grower.

In addition, Kittas et al. [53] studied the effect of UV-absorbing covering films on tomato soilless crops. Experiments were conducted during spring and summer. Three plastic covers with UV transmission 5% (common), 3 and 0%, were used. The results revealed that the reduction of the incoming UV resulted in a small increase of internodes length, plant height and plant total dry matter production. Furthermore, the reduction of UV radiation caused a significant increase of the crop leaf area index (which means higher cooling process). Moreover, it should be mentioned that the reduction of the UV in greenhouse interior space did not affect bumblebee activity.

Krizek et al. [54] studied the inhibitory effects of ambient levels of solar UV-a and UV-b radiation on growth of cv. New Red Fire lettuce. Plants were grown from seed in plastic window boxes and the findings revealed that UV-b radiation is more important than UV-a for flavonoid induction in this red-pigment lettuce cultivar.

Garcia-Macias et al. [55] investigated the changes in the flavonoid and phenolic acid contents and antioxidant activity of Red Leaf Lettuce (Lollo Rosso) due to cultivation under plastic films varying in UV transparency. The results demonstrated the potential of the use of UV-transparent plastic as a mean of increasing beneficial flavonoid content of red leaf lettuce when the crop is grown in polytunnels.

Oh et al. [56] studied antioxidant phytochemicals in lettuce grown in high tunnels and open field. It was found that lettuce grown in open field with higher solar radiation and possibly higher UV, had higher transcript levels for phenylalanine ammonia-lyase (PAL), L-galactose dehydrogenase (L-GalDH) and γ-tocopherol methyl transferase (γ-TMT), all involved in the biosynthesis of antioxidants.

Paul et al. [57] studied the use of wavelength selective plastic cladding materials in horticulture in terms of crop (and fungal responses). The responses of a range of crops to plastics that have either (a) increased transmission of UV compared with standard horticultural covers, (b) decreased transmission of UV or (c) increased the ratio R/FR (Red/Far Red) radiation, were studied. UV-transparent as well as R/FR increasing films reduced leaf area and biomass, offering potential alternatives to chemical growth regulators. The UV-opaque film increased growth, but while this may be useful for some crops, there might be trade-offs with elements of quality, such as pigmentation and taste. The study showed that in lettuce, the model species, UV transparent film was as effective as the R/FR-modifying film in reducing growth while growth was stimulated under UV-opaque film compared with the standard film. The capacity for UV modification within the ambient range to control growth has a physical basis and photobiological literature suggests that plant responses to UV manipulation vary between species or genotype. Furthermore, manipulating UV influenced the taste of lettuce; the increasing UV resulted in a more intense, bitter taste. Increasing UV may increase the volatile oil content of some herbs; however, in the above mentioned investigation which included five species of herbs, only one (peppermint: *Mentha piperita*) showed any significant increase in oil concentration in responses to UV-modifying films over two growing seasons. UV modification leaded to clear increases in the pigmentation of red-leafed lettuce with increasing UV. Such increases in anthocyanins are typical of the effects of modification of solar UV on a range of pigments and antioxidants many of which have a nutritional role in the human diet.

Kishima et al. [58] investigated the wavelength range that activates betalain pigmentation following selection of light inducible betalain producing callus lines originating from *Portulaca* sp. 'Jewel' seedlings. Light sources with different wavelengths were used to irradiate the callus, resulting in blue light being effective in inducing betalain pigmentation. When UV light was combined with blue light, some calluses from this cell line showed high production of the pigment and this is a first report that betalain pigmentation in callus was induced by blue and blue/UV lights.

On the other hand, the benefits of supplementary ultraviolet radiation (UV-b) in protected lettuce were investigated in controlled environment studies by Wargent et al. [59]. Exposure to UV-b prior to inoculation with a conidial suspension of *Bremia lactucae* (lettuce downy mildew) led to significant reduction in the subsequent sporulation of the pathogen. UV treatments increased leaf thickness, reduced leaf area and increased leaf pigmentation in a red-leaved cultivar. It should be mentioned that such changes in leaf area and thickness are important quality factors and would be expected to improve plant performance after transplantation into the field.

Six types of PE sheets (with or without a blue pigment) with absorption peak at the yellow part of the spectrum (580 nm), in combination with three levels of UV-b absorbance, were investigated by Reuveni and Raviv [60], in terms of their effects on sporangial production and colonization of *Pseudoperonospora cubensis* on cucumbers in growth chambers. The addition of the blue pigment to the films leaded to a significant inhibition of colonization and sporangial production of *P. cubensis*, while filtration of the UV enhanced the colonization but had no effect on the sporangial production. The appearance of the first symptom-bearing plants was delayed under the blue covers and a significant reduction in the disease incidence of downy mildew was showed under all blue sheets at each corresponding level of UV-b transmittance in field experiments (four seasons). Regardless the differences in disease incidence, there were no significant differences among the yields that were obtained under the various sheets, probably due to the lower PAR transmissivity of the blue films.

Another study in this field is that of Chen et al. [61]. Modified vinyl-[polyhedral oligomeric silsesquioxane (POSS)] (VP) materials were investigated. The average transparency of the films measured at the ranges of UV-a and UV-b spectra was about 45.43–48.71%, indicating that these films can protect greenhouse plants from UV-a and UV-b. Finally, it should be mentioned that POSS/TiO_2 nanohybrids as sun protection ingredients for greenhouses have also been studied by Wang et al. [62].

3.3.2. UV-blocking and detrimental insects

UV-radiation manipulations such as the use of UV-blocking cladding materials provide a challenging solution for IPM in greenhouse-grown crops. The mechanisms of the protective effects of UV-absorbing covers are related with the wavelength-dependent behavior of insects which is driven by several different spectral classes of receptors, including those sensitive in the UV range. It has been found that there is a positive correlation between the amount of UV filtration and the level of protection against insects since insects fail to orient themselves within the UV-deficient environment of protected structures covered with UV-absorbing materials. For example the dramatic decrease in the incidence of whitefly-borne viruses under UV-absorbing cladding materials may be the result of reduced activity (movement or feeding) of whiteflies, leading to a decrease in virus spread. Certainly, an interesting aspect of this kind of techniques is the protection against insect-born viruses and general pathogens without using pesticides [63].

On the other hand, UV radiation is the most crucial factor for the degradation of greenhouse films; therefore, it is usual to include in their formulation UV absorbers as stabilizers. However, the usual amount of UV absorbers is not enough when specific effects are pursued such as the above mentioned ecological techniques against specific pathogens of greenhouse crops. Therefore, extensive research has been carried out in order to investigate this type of cladding materials and their effects on detrimental insects as well as on pollinator insects. Aspects such as the effects of UV radiation on: insect vision/behaviour; plants; insect herbivores; strategies for IPM production systems, have been studied [64]. Following several representative works, in the above mentioned field of research, are presented.

In terms of the greenhouses of the northeastern Spain, Díaz et al. [51] studied the impact of UV-blocking plastic films on insect vectors of virus diseases infesting crisp lettuce. A 2-year experiment was conducted in Spain (Navarra). The results revealed that the UV-absorbing plastic film did not loose its ability to filter UV after three lettuce crop cycles. The tested film was effective in reducing the abundance as well as in delaying the colonization of lettuce by aphids (*Macrosiphum euphorbiae* and *Acyrthosiphum lactucae*). A reduction in the number of the plants infested by aphids and by insect-transmitted virus diseases was observed. The tested films were also effective in reducing the population density of *Frankliniella occidentalis* and the spread of tomato spotted wilt virus as well as the population density of the lepidopteran pest *Autographa gamma* which is a common pest of lettuce in Spain. Nevertheless, the control of the whitefly *Trialeurodes vaporariorum* was not effective. Conclusively, the results of this study revealed that the UV-absorbing plastic films are promising for the protection of greenhouse lettuce from the main pests and the insect-transmitted virus diseases of northeastern Spain.

Lettuce was also studied by Legarrea et al. [65]. Spatio-temporal dynamics of aphid-transmitted viruses and its vector were investigated for the case of lettuce (*Lactuca sativa* L.) grown under tunnels covered with two types of nets: a commercial UV-absorbing net (Bionet) and a Standard net. Plants infected by Cucumber Mosaic Virus (CMV, family Bromoviridae, genus Cucumovirus) and Lettuce Mosaic Virus (LMV, family Potyviridae, genus *Potyvirus*) were transplanted in each plot. The same virus-infected source plants were artificially infested by the aphid *M. euphorbiae* (Thomas) and the secondary spread of insects was weekly monitored. Infection rate of both CMV and LMV were lower under the Bionet than under the Standard cover, probably because of the lower population density and lower dispersal rate achieved by *M. euphorbiae*. However, for other tests (during spring) significant differences in the rate of infection between the two covers were only found for LMV six weeks after transplant. Conclusively, the results showed that UV-absorbing nets can be recommended as a component of an integrated disease management program for the reduction of the secondary spread of lettuce viruses, although not as a control measure on its own.

Green peach aphid, *Myzus persicae* (Sulzer) (Homoptera: Aphididae), was studied by Chyzik et al. [66]. Laboratory and field experiments were conducted to determine the effect of UV filtration on the population growth, distribution and flight activity of the green peach aphid as well as on the fecundity and host-finding behavior of the parasitic wasp *Aphidius matricariae* (Haliday) (Hymenoptera: Braconidae). The work was conducted in the Arava Valley of Israel, in walk-in tunnels covered with polyethylene film, in order to compare the effects of UV-absorbing film versus those of regular film. Following artificial aphid infestation on pepper grown (under the tested films), the population of the aphids which was grown and spread under the UV-absorbing films was significantly less than under the regular films. The greatest impact of UV-absorbing film on aphid behavior was observed during winter and early spring (when the temperature conditions favor aphid development). The elimination of UV by UV-absorbing film did not affect the parasitic activity of *A. matricariae*. Previous results indicated that covering the greenhouse with UV-absorbing films inhibited the invasion of aphids and other insect pests into the greenhouse.

Antignus et al. [67] studied whitefly attraction and flight-behavior under regular and UV-absorbing plastic sheet tunnels. The findings revealed that the rate of Tomato Yellow Leaf Curl Virus (TYLCV)-disease spread to tomato plants, grown under walk-in tunnels covered with regular greenhouse plastic sheets, increases sharply with time whereas the virus infection-rate under UV-absorbing sheets proceeds at a very slow pace. On the other hand, no differences were found in the whiteflies ability to transmit TYLCV under the two types of plastic covers. Furthermore, a release-recapture experiment was conducted to examine whitefly dispersal pattern under the two types of plastic covers. In each type of walk-in tunnel, a grid of yellow-sticky traps forming two concentric circles: an inner and an external, were established. Under UV-absorbing tunnels, significantly higher numbers of whiteflies were captured on the internal circle of traps than the external circle. The fraction of whiteflies which were captured on the external circle was much higher under regular covers when compared with UV-absorbing covers, revealing that filtration of UV light hindered the ability of whiteflies to disperse inside these plastic tunnels. In Fig. 8, the average numbers of whiteflies per sampling date trapped on yellow sticky traps placed inside non-UV absorbing (IR) and UV-absorbing (IR-UV) walk-in tunnels, are illustrated. The average numbers of whiteflies trapped per sampling period under IR plastic sheet tunnels was significantly higher than the ones trapped in IR-UV plastic sheet tunnels in seven of eight times tested. The differences in trapped whiteflies between the two types of plastic sheet walk-in tunnels were greater 38 days after planting. Conclusively, the results of Antignus et al. [67] indicate that the blocking of UV light protects covered crops from infestation by insects and spread of viruses in at least two ways: (a) insects are not attracted to structures lacking UV and fewer insects invade greenhouses covered with UV-absorbing cladding material, (b) the lack of UV radiation alters the normal behavior of the invading insects, leading to reduced flight activity. In this way, the efficiency of virus transmission is reduced.

Mutwiwa et al. [68] also studied the effects of UV-absorbing plastic films on greenhouse whitefly (Homoptera: Aleyrodidae) (orientation and distribution behavior of the greenhouse whitefly, *T. vaporariorum* (Westwood)). Small tunnels were constructed and covered with either UV-transmitting (Thermilux) or UV-absorbing (*K*-Rose) plastic films. The results did show that

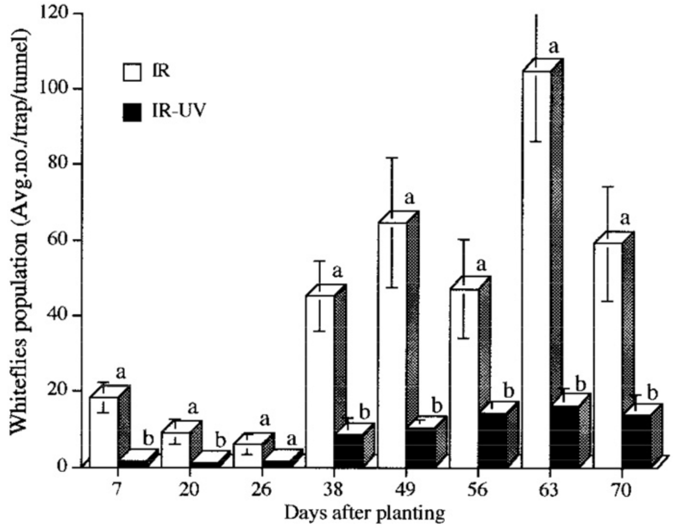

Fig. 8. Trapping of whiteflies in tunnels covered with regular (IR) or UV-absorbing (IR-UV) polyethylene sheets (tomato plants were grown and two yellow sticky traps were placed in each tunnel, for whitefly monitoring) [67].

significantly more whiteflies were recorded in the tunnels with high compared with those with low UV intensities. In addition, whitefly penetration and dispersion were less inside the UV-deficient tunnels. Thus, the type of plastic film used for greenhouse covers may have a significant influence on the initial immigration and distribution of *T. vaporariorum* in a greenhouse and thereby these films can be adopted in the frame of IPM.

For the case of greenhouses of southeastern Spain, López-Marin et al. [69] conducted a study about the effect of UV-blocking plastic films on insect vectors of virus diseases infesting tomato (*L. esculentum*) in greenhouse. Tomato Spotted Wilt Virus (TSWV) is transmitted in a persistent propagative manner by *F. occidentalis* (Pergande) (Thysanoptera: Thripidae), the western flower thrips. Experiments were conducted in southeastern Spain (Murcia) in order to evaluate the impact of a UV-blocking film on the population density of *F. occidentalis*. Tomato plants were subjected to four different treatments causing a reduction in incoming UV-a radiation. Sticky traps (of different hues) were used to control/monitor the population density of thrips. The results revealed that UV-absorbing plastic films are promising claddings for the protection of greenhouse tomato from thrips pests occurring in southeastern Spain.

Doukas and Payne [70] investigated the use of UV-blocking films in insect pest management in UK. Studies in polytunnels were conducted and the effects of UV-blocking films (blocking light <385 nm) on naturally occurring insect pests and their arthropod natural enemies on a cucumber crop, were investigated. When all the plants within the UV-transmitting (UVI/Ethyl Vinyl Acetate (EVA)) tunnels had become heavily infested with aphids, half of the plants in UV-blocking (XL 385) tunnels were not infested. More Coleoptera and thrips (approximately two times) were recorded under the UV-transmitting film than under the UV-blocking films, but for other arthropod pests (e.g., whitefly, leafhoppers) there were clear conclusions because low numbers were recorded. Substantial numbers of chalcid parasitoids and syrphids were found under the UV-blocking films, but further research is needed to evaluate fully the effect of such films on biological control of aphids. Higher syrphid numbers and more aphid mummies were recorded under the UV-transmitting film, probably because of the higher numbers of aphids present in tunnels clad with this film.

Moreover, a recent study of Nishizawa et al. [71] regards UV-blocking and insect control. Cucumber (*Cucumis sativus* L. 'Hiryu') and tomato (*L. esculentum* L. 'Momotaro') plants were grown under four different polyolefin film greenhouses (0.15 μm thickness). The UV wavelengths shorter than 400, 360, 350 and 340 nm, respectively were blocked while a standard polyolefin film greenhouse was used as control. The control greenhouse achieved approximately 50% blocking of the UV. However, under partial UV blocking conditions more than 70% UV blocking was achieved. Nine different insects were captured on the adhesive films (fly, rice plant hopper, whitefly and aphid were mainly captured on yellow adhesive films, while hoverfly was mainly captured on blue adhesive films). It should be mentioned that the effects of the specific UV-blocking films were most obvious for aphid control. The results of this study showed that specific UV-blocking plastic films are commercially acceptable for promoting IPM systems especially for aphid control without harming the growth of the plants.

Another recent study about UV-absorbing films and nets and the dispersal of western flower thrips, *F. occidentalis* (Thysanoptera: Thripidae) is that of Kigathi and Poehling [72]. In the frame of this work the effects of such materials on the dispersal behavior of Western Flower Thrips (WFT), *F. occidentalis*, in flight cages under greenhouse conditions with additional artificial UV-a light sources, were investigated. Different trapping methods were compared (blue sticky cards, plants and transparent cards) in terms of the recapture of the thrips. In choice experiments, the insects were released from a black box compartment between two tunnels covered with UV-transmitting or UV-absorbing claddings. A significantly higher proportion (82–98%) of WFT was recaptured in the UV-transmitting tunnels compared with the UV-absorbing tunnels. Other experiments such as "no-choice" etc were also conducted. Conclusively, the manipulation of the spectral light properties by using UV-absorbing cladding materials for protected crop stands interferes with the orientation and host finding of WFT, leads to reduced dispersal into and within plant stands in UV-deficient environments.

In addition, another study about physical means of IPM refers to the efficiency of insect screens and photoselective covering materials on insect population control [73]. Experiments were performed from 2000 to 2004 in three greenhouse tomato, PE-covered greenhouses. The ventilation inlets of the first greenhouse were covered by an insect screen while the second greenhouse was used as control. In terms of the photoselective covering materials, two UV-absorbing PE films (0 and 3% UV transmission) along with a common PE film were used for the three greenhouses (three-year experiment). The results revealed that the insect screen on greenhouse ventilation openings, prevented aphids from flying into the greenhouse and significantly restricted the number of thrips inside the greenhouse (however, it did not influence whitefly population). With the UV-absorbing PE films, a lower number of thrips and aphids were caught in the greenhouse with 0% UV transmission than those in the other greenhouses. Differences regarding the efficiency were observed between the PE films during the time of insect population control. It was found that none of the two UV-absorbing PE films which were tested had an adverse effect on the activity of bumblebee pollinators. Although, no significant effects of photoselective materials were found on greenhouse microclimate, the use of insect screens reduced considerable greenhouse ventilation and increased its air temperature.

The effect of UV-absorbing plastic sheets on the host location ability of three commercially available parasitoids *Aphidius colemani* Viereck (Hymenoptera: Braconidae), *Diglyphus isaea* Walker (Hymenoptera: Eulophidae) and *Eretmocerus mundus* Mercet (Hymenoptera: Aphelinidae), was tested (in the laboratory and

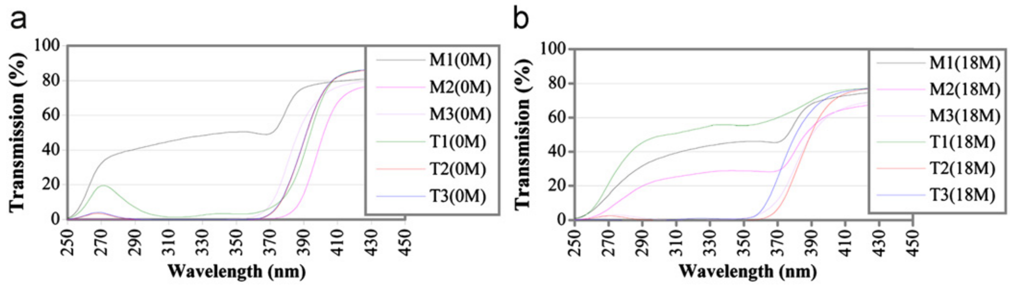

Fig. 9. UV–VIS spectrum of tested plastics: (a) before and (b) after eighteen months exposure outdoors [76]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

in field trials) by Chiel et al. [74]. The parasitoids preference between natural light and UV-filtered light was investigated under laboratory conditions in a Y-shaped pipe system and the vast majority of all three species were strongly attracted to non-UV-filtered light. On the other hand, in field trials parasitoid ability to locate a host-infested plant from a distance (approximately 10 m), was tested. Host location by *A. colemani* and *D. isaea* (expressed by parasitization rates) was not affected by greenhouse covering plastic type (regular versus UV-absorbing plastic) while *E. mundus* was unable to locate the host-infested plant when the latter was placed in the center of the UV-absorbing plastic covered greenhouses. When the host-infested plants were located in the greenhouses corners and the wasps were released at the center, the parasitization rates were lower under the UV-absorbing plastic than under the regular plastic covered greenhouses. Conclusively, the study of Chiel et al. [74] demonstrated that UV-absorbing plastic sheets and screens can be used concurrently with *D. isaea* and *A. colemani*, without interruption of their host location ability. *E. mundus* should probably be introduced in multiple release points, or as close as possible to the *B. tabaci* infested plants, in order to facilitate its host location process.

Krizek et al. [75] characterized the spectral properties of selected UV-blocking and UV-transmitting covering materials by means of a UV–VIS (UV–Visible) spectroradiometer or a UV–VIS spectrometer. The study provides guidelines for the researchers and the growers because the selection of suitable materials is related with the effect of ambient solar UV radiation on the production of tomatoes and other high-value crops in high tunnels. The survey included a wide range of plastic covering materials and commercially available products that have desired characteristics of transmitting high levels of PAR and being stable under ambient solar UV radiation. The study was focused on the evaluation of films that either block or transmit UV wavelengths below 380 nm in order to determine comparative growth, yield and market quality and provide a tool for IPM.

On the other hand, an increasing demand of tri-layer films has been observed in terms of three agricultural season duration. Due to currently existing formulations it is not possible to reach an antipest effect for three agricultural seasons with monolayer films. González et al. [76] tested several new tri-layer films in real conditions, to determine their UV opacity, antipest effectiveness and influence on the pollinator insect performance. Improved duration of the UV-blocking effect occurred with the new filters used and in most cases the yield obtained with UV-blocking films was higher than with normal films. The following films were tested: M1 (reference film, monolayer, polymer: Low-density polyethylene (LDPE), no UV absorber), M2 (monolayer, polymer: LDPE, UV absorber: Benzophenone/ Benzotriazole), M3 (monolayer, polymer: LDPE, UV absorber: Triazine 1), T1 (tri-layer, polymer: EVA, UV absorber: Benzotriazole), T2 (tri-layer, polymer: EVA, UV absorber: Triazine (1), T3 (tri-layer, polymer: EVA, UV absorber: Triazine (2). In Fig. 9, the evolution of UV opacity of the tested films is illustrated. After 18 months in the field M3, T2 and T3 maintained a good UV opacity. In terms of covers effect on detrimental insects, in both trials, lower populations of adult *B. tabaci* and *F. occidentalis* were detected under the UV-blocking monolayer films. In the first trial, there were between 55 and 82% less thrips under the UV-blocking film than under the reference one while in the second trial there were between 16 and 64%. However, a higher presence of *B. tabaci* was observed under the tri-layer films, probably due to the higher temperature under this kind of films. Regarding the effect of covers on viral diseases, in the first trial Cucumber Yellow Virus (CuYV) did not affect any plant, thus it was not possible to evaluate the effectiveness of the different covers for this case. In the second trial, a significant lower incidence of TYLCV was detected for the crop grown under the UV-blocking monolayer plastic films as well as under the UV-blocking tri-layer plastic film T2. Furthermore, there was poor incidence of TSWV. Finally, the effect of covers on plant characteristics and yield was also investigated. In both trials, UV-blocking films, with the exception of M3, showed better performance and higher yield (14–19% more) than the reference film (M1). In the second trial, a higher production was obtained under the tri-layer films. Regarding the monolayer films, M2 was the film with the lowest *F. occidentalis* and *B. tabaci* population, lowest number of plants infected by TYLCV and highest yield in both trials, with melon and tomato. In terms of the tri-layer films the differences were not clear. Results for the third agricultural season are needed in order to present final conclusions. In the second trial, the yield was higher under the tri-layer films, although monolayer and tri-layer films were not comparable due to the different characteristics such as higher PAR transmission and temperature under the films.

3.3.3. UV-blocking and bumblebees

Bees often facilitate pollination of important greenhouse crops. For example, bumblebees *Bombus* spp. are commonly used as pollinators of greenhouse tomato, *L. esculentum* Mill. (Solanaceae) and of several other crops, instead of using other methods such as electronic vibrating. In general, bumblebees are essential pollinators of angiosperms and through UV radiation use their vision to detect the flowers. Given the sensitivity of bees to UV radiation, there are some studies in the literature which focus on the ability of bees to operate visually under UV-blocking greenhouse covers.

In the study of González et al. [76] (Section 3.3.2) the effect of covers on pollinator insects was also investigated. At the end of the first trial only the greenhouse covered with non UV-blocking film maintained the initial number of bumblebees. In the other greenhouses, the number decreased to a half or a quarter. In the end of the trials, all the UV-blocking films had less set fruits than the reference one. Certainly, this finding fits with the number of bumblebees remained in the beehive.

Dyer and Chittka [77] investigated bumblebees search time without UV light. In the frame of this study, bumblebees *Bombus terrestris* L. were housed in a two-chamber wooden nesting box connected with a Plexiglass tube to a flight arena. Individual bumblebees *B. terrestris* were tested in the indoor flight arena to evaluate whether or not search time to find flowers was influenced by the inclusion or exclusion of UV radiation. Plastic model flowers of similar spectral properties to flowers of tomato *L. esculentum* Mill, were used to evaluate bee search efficiency. The findings of the work revealed that bumblebees perceive when UV radiation is either removed or added to an illumination source; however, the bumblebees rapidly learn to find model flowers with equal efficiency in either illumination environment. The behavioral results are interpreted in relation to a colorimetric analysis showing how bumblebees are capable of using their visual system to forage efficiently in environments which exclude UV radiation.

Morandin et al. [78] studied the actitivity of bumblebees (*Bombus impatiens* Cresson) in commercial tomato (*L. esculentum* Mill, Solanaceae) greenhouses in terms of greenhouse covering type, solar radiation, greenhouse temperature and humidity. The investigated types of covers were grouped into four categories: (1) Patilux (Pati Corporation, Armin Films, City of Industry, California); (2) AT Bee Plastic (AT Plastics, Brampton, Ontario) and De Klerk (Klerk's Group, Richburg, South Carolina); (3) AT Duratherm 3 (AT Plastics); and (4) CT (Huntsman Films, Salt Lake City, Utah). AT Bee Plastic and De Klerk were grouped together because of their similar light-transmission spectra. Four of the covering types were chosen due to the fact that they are among the most commonly used in the Leamington area. CT plastic was chosen due to its high degree of UV transmittance and because of verbal reports from growers of high levels of bee activity under this type of covering. Spectral distributions were measured in commercial greenhouses using an LI-1800 portable spectroradiometer and the results are depicted in Fig. 10(a). Pairwise comparisons between the above mentioned types of covering showed that bees under CT plastic took, on average, twice as many daily trips as bees under the other three types of plastic (an average of 4.8 daily trips per bee under CT plastic vs. an average of 2.4 under the other three types of claddings) (Fig. 10b). Bumblebees activity was measured by photodiode monitors inserted into the entrance of the colonies while colony sizes were monitored as an indicator of bee loss through gutter ventilation systems in relation to covering. Activity monitors were found to be a good predictor of actual bumblebees entrances and exits (r^2=0.85). Bumblebees activity was 94% greater under the UV-transmitting cover than under the covers which transmitted less UV light. It should be mentioned that no relationship was found between bees activity and the amount of solar radiation or internal greenhouse humidity while bee activity was weakly positively correlated with internal greenhouse temperature (r^2=0.18). Furthermore, bumblebees activity was not different during morning, midday and evening. Conclusively, the results of the above mentioned work revealed that bees activity was greatest and bees loss through gutter ventilation systems lowest in greenhouses with coverings which transmit high levels of UV light.

On the other hand, Morandin et al. [79] conducted laboratory experiments in order to study the relationship between commercial greenhouse PE coverings and bumblebee, *B. impatiens* Cresson (Hymenoptera: Apidae), activity and loss from ventilation systems. Bee activity was measured in four small greenhouses, each with a different PE covering and quantified using photodiode tunnels mounted in the hive entrances. Contrary to commercial greenhouse experiments, there was no difference in bee activity based on covering type. Finally, similar to other studies, there was a positive linear relationship between temperature in the experimental greenhouses and bee activity. The potential for bee loss through open ventilation systems for five covering types was quantified by means of a Y-maze decision box. Bees were more attracted to direct light than to light transmitted through UV-blocking coverings, whereas bees were equally attracted to direct light as they were to UV-transmitting coverings. These experiments reveal that greenhouses with UV-transmitting plastics may result in less bee loss through ventilation systems. Bumblebees under coverings that transmit more UV light may perceive less visual contrast between light from open greenhouse vents and transmitted light than in greenhouses with UV-blocking coverings. This may result in fewer bees lost through open ventilation systems. It should be mentioned that contrary to authors' expectations, bees were not more active under high UV transmitting coverings. The findings of the present work was contrary to data collected from commercial tomato greenhouses [78], perhaps due to the fact that the miniature greenhouse design was not sufficient to detect differences in bee activity based on light transmission. Thus, further studies on the effects of covering type on bee activity conducted in larger experimental greenhouses, using plants rather than foraging arrays, would be beneficial.

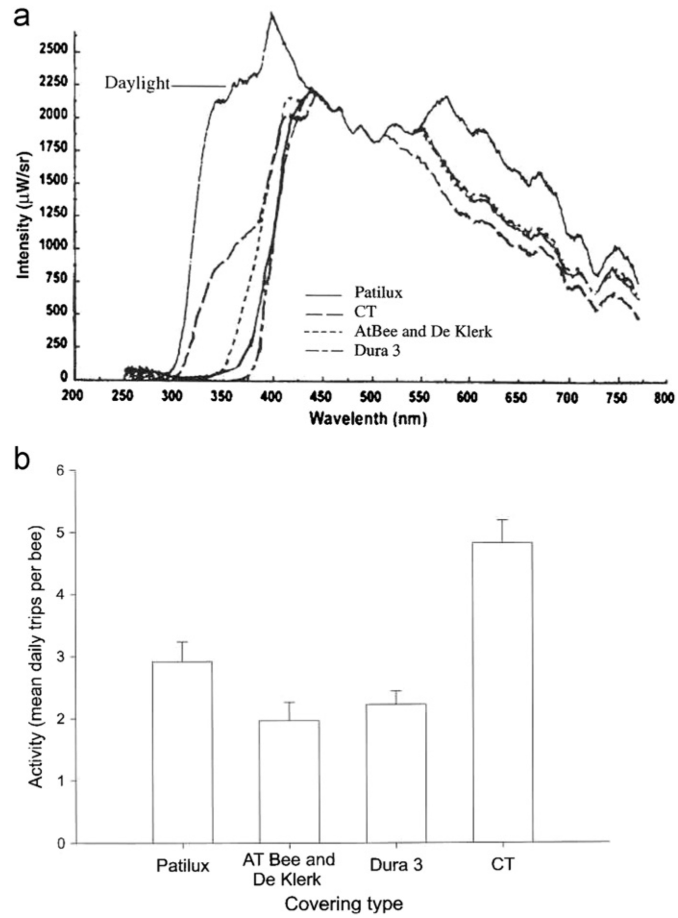

Fig. 10. (a) The spectral distributions of daylight and light transmitted through the five types of commercial greenhouse covering in the Leamington, Ontario, area recorded using a LI-1800 portable spectroradiometer, (b) Mean+standard error (SE) *Bombus impatiens* activity measured at the hive entrance of five colonies under the four types of commercial greenhouse polyethylene covering [78].

3.3.4. UV-blocking and fungus

Given the fact that high Relative Humidity (RH) is common in most greenhouses, coverings which can reduce RH, and thus

Botrytis cinerea, by reducing greenhouse cooling during the night could be beneficial [80]. Certainly, this kind of antipest films shows great interest and extensively research has been carried out. Following are given representative references from the literature about UV-blocking cladding materials for fungi control.

Honda [81] investigated the control of seedling blast of rice with UV-absorbing vinyl film. The results showed that almost 99% of 386 monoconidial isolates of *Pyricularia oryzae* were light-dependent for sporulation, whereas only 1% (four isolates) were light-independent. Without fungicides, rice (*Oryza sativa*) seedling blast incidence in the nursery at the four-leaf stage was reduced to less than 10% in a UV-absorbing vinyl film greenhouse compared with incidence levels in a common vinyl film greenhouse.

Nicot et al. [82] compared several samples of PE films containing additives that absorb near UV (nUV) in the range 280–380 nm in terms to their ability to affect spore germination, mycelial growth and sporulation of *Botrytis cinerae* on agar medium. One film was selected and further investigated. The kinetics of spore production by the pathogen was similar on agar medium as well as on tomato stem tissue and whether incubation took place under the nUV-absorbing film or under a control film. However, spore production on both types of substrates under the nUV film remained at less than 0.05% that of the control for several weeks after inoculation, revealing that the nUV film inhibited rather than delayed sporulation. Furthermore, a sharp reduction of spore production was also observed on the other plant tissues. However, the efficiency of the nUV film appeared different for different plants and it was lower for flowers and cotyledons than for stem tissue. In addition, two of the five strains of *B. cinerae* tested on tomato stem tissue were less sensitive to sporulation inhibition by the nUV film. Conclusively, to clarify the potential of nUV films for the control of gray mold on greenhouse crops, the epidemiological significance of these results needs to be further examined in light of the abundance of such strains in the environment.

Sasaki and Honda [83] studied the control of certain disease of greenhouse vegetables with UV-absorbing vinyl film. The use of UV-absorbing vinyl film for controlling diseases caused by *Altenaria dauci*, *A. porri*, *A. solani*, *Botrytis squamosa* (UV-induction group) was attributed to the elimination of the inductive UV radiation. Disease control for *Stemphylium botryosum* as well as *A. brassicae* (light inhibition group) was accomplished by filtering out UV radiation that would otherwise nullify blue light inhibition. Of four fungal species in the UV-induction group with respect to sporulation response to monocromatic radiation, three species of Altenaria did not sporulate under conditions of white light. Successful control of the diseases caused by *S. botryosum* and *A. brassicae* with UVA-vinyl suggested that light inhibitory to sporulation would control the disease in the greenhouse. The effect of UVA-vinyl on disease control was attributed to accentuation of the inhibitory blue light effect by filtering out UV radiation from sunlight.

Sporulation of *B. cinerea* was studied in vitro by Reuveni et al. [84], under various filters and PE co-polymer sheets. PE sheets with several additives incorporated into the sheets in order to modify their spectral transmittance, were studied. The UV-absorber was hydroxybenzophenon and two celluloid filters were used either to transmit only blue light or to absorb all the blue light. It was found that continuous darkness blocked sporulation completely and sporulation was inhibited by reduced UV radiation. Furthermore, almost total inhibition of sporulation was also found when cultures were grown under a blue filter and the reduction of spore formation was negatively related to the ratio of transmitted blue/UV light. Blue light inhibition of sporulation in *B. cinerea* is initiated by conversion of a mycochrome to a form which inhibits sporulation [85]. The findings of Reuveni et al. [84] are in agreement with the hypothesis formulated by Tan [85]. Furthermore, it should be noted that the mere exclusion of UV radiation does not prevent spore formation as long as blue light transmittance is low. Similarly, reduction in the transmitted blue light resulted in a higher level of sporulation even when the blue/UV ratio was relatively high. Although the light emission spectrum of the lamps within the growth chamber was quite different from that of the sun, the overall conditions in the growth chamber represented natural conditions more realistically compared to short pulses of monochromatic light. Conclusively, a high ratio of blue/UV transmitted light through greenhouse cladding materials may provide a new solution for the reduction of *B. cinerea* incidence on various protected crops.

Elad [86] tested new custom-made PE films with light blockers in the FR region of the spectrum in terms of their effect on sporulation of *B. cinerea.* A pink-pigmented PE sheet partially screened visible light mainly from 470 to 650 nm, with lowest transmissibility at 500–580 nm, and a green-pigmented sheet partially screened it mainly from of 560 to 800 nm, with lowest transmissibility at 600–700 nm, were investigated. The results showed that filtration of light in the UV range supplemented with partial exclusion of radiation in the FR region by the green PE film, effectively reduced the sporulation of pathogen cultures. The dark or combined green and pink films totally suppressed sporulation in some cases while sporulation suppression was more pronounced than conidiation suppression when the fungus was incubated under the black film. The effect of the dark filters could be attributed not only to the reduction of sporulation-inducing irradiation but also to an indirect effect on the host tissue. Such an effect on the host tissue can render it less hospitable to the sporulating *B. cinereu* thallus by limiting the essential compounds supply for the fungus. Filtered light and black films affected sporulation on cucumber fruit slices as well as tomato leaflets as described above. On the other hand, sporulation suppression on potato dextrose agar (PDA) cultures was generally the same under filtered light and black film, which could be attributed to the fact that no host influenced the system. Implementing light filtration by using the light green pigmented PE cover was tested in several greenhouses (under commercial conditions) and the conidial load was only partially reduced. Disease was reduced by 35–75% on tomato and cucumber fruits and stems; the effect on disease was associated in most cases with conidial load reduction in the greenhouses. However, reduction in the population of conidia did not necessarily result in parallel reduction in disease incidence. The partial effect of the new green film on disease incidence could be attributed to: insufficient reduction of the population of conidia as a result of incomplete screening of the inductive range of light irradiation; infiltration of reflected solar light via openings in the greenhouse; variation in the response of pathogenic isolates to sporulation-inducing light; the presence of isolates which are capable of sporulating in the dark; nutritional reversal of inhibition by host tissue infected in the greenhouse. In addition, the load of conidia in greenhouses is usually high, so the number of conidia is not a limiting factor in conventional greenhouses; even when reduced under the green PE, the conidia population is sufficient to endanger the crop. Only a very pronounced reduction in production of conidia in the greenhouse can lead to significant disease control during the whole season. Thus, suppression of sporulation may only delay epidemic development; with continued use of photoselective film, selective pressure toward populations containing a larger proportion of pathogenic isolates not dependent on light for sporulation induction, could be faced. The green-pigmented film may contribute to integrated disease management in greenhouses, contributing to reduction in the use of fungicides to control *Botrytis spp*.

Paul et al. [87] conducted a UV-manipulation study for disease control and showed that increasing UV inhibited not only the pathogenic fungus *B. cinerea* but also the disease biocontrol agent *Trichuderma harzianum*. It should be mentioned that unlike *B. cinerea*, *T. harzianum* was highly sensitive to UV-a radiation. The above mentioned fungal responses and those for plant growth in the growth room and the field under different plastics were analyzed in terms of alternative biological spectral weighting functions.

3.3.5. UV-blocking and rose petal blackening

UV-b followed by low leaf temperatures results in petal blackening of red rose cultivars (dark coloration on the outer petals), causing considerable financial losses to the growers. The accumulation of a high content of a dark pigment concentrated at the petal tip (so that it appears almost black) is a phenomenon which becomes apparent either before or after marketing. These flowers are rejected or downgraded at the packaging house or destroyed after shipment, leading to severe financial losses. However, by using the proper UV absorber at the required concentration in the plastic film of greenhouse covers, the blackening of red roses can be prevented [88].

Aguyoh et al. [89] conducted a study in order to investigate the influence of greenhouse cover material on insect pest infestation, powdery mildew and rose petal blackening. The experiments were carried out in three commercial rose farms in Kenya (Kericho, Eldoret and Juja) and the research was carried in two phases: field survey with most information being collected through structured questionnaire and on site tests. The results showed that rose petal blackening was not associated with any type of greenhouse cover, but was dependent on the age of the cover material. The highest number of mites (15.7 mites/plant) was observed at the Juja flower farm, area with high temperatures. Powdery mildew infection was significantly high in the three year old PE covered greenhouses compared to the level of infestation in the greenhouses with new covers. In terms of the spectral transmission properties of the greenhouse covering materials tested, the amount of solar energy transmitted to the plant canopy was influenced by the position at which the radiation was taken. As the covering material ages, the percentage of petal blackening of roses as well as powdery mildew increased, thus the quality of the flowers was affected. The increase in powdery mildew with the aging of the covering material could be attributed to the dependence of the sporulation of some fungi on UV light.

3.3.6. Critical issues

From the above mentioned studies about UV-blocking materials it can be seen how these claddings are related with several aspects such as plants growth, detrimental and pollinator insects, fungus sporulation, red rose petal blackening. UV-blocking covers can be adopted in the frame of IPM providing an environmental-friendly solution for pest management. Nevertheless, these claddings should be used after a preliminary testing for several cases: for example when bumblebees are used as pollinators; when for the pest control beneficial insects are utilized; when the crops are eggplants or other purple plants. Certainly, factors such as the humidity and the temperature of the air of greenhouse interior space play an important role in the development of diseases and by using a specific cover does not necessary implies effective control of the diseases.

4. Conclusions

In the present paper, some critical types of greenhouse covering materials which can cause sunlight manipulations are reviewed. First are presented Fresnel lenses (FL), thin lenses (similar to conventional) which can be integrated into greenhouse south roof and can be combined e.g., with Concentrating Photovoltaic Thermal (CPVT) systems. The advantages are: temperature and light control (because FLs have the ability to separate direct from diffuse radiation) with parallel production of heat and electricity for greenhouse energy needs. In the literature have been reported recent studies about this type of greenhouses and the results show that these solar energy systems are promising. At this point it should be noted that for the case of active FL systems, the use of 2-axis tracking systems should be avoided since increases not only the cost but also the complexicity and the weight of the set-up. Conclusively, in order to compensate the cost and the efficiency, the use of FL combined with 1-axis tracking and simple Concentrating Thermal (CT) system for light/temperature control and production of heat seems to be a cost-effective and promising option.

Regarding other types of coverings, NIR-blocking claddings refer to several and different categories: solar concentrators, PE films, fluid roofs etc. These covers provide a cooling effect which is beneficial for areas with high solar radiation (in mild climates NIR-filtering is not desirable during winter) or for nurseries and shade-loving plants. However, the cost and the reduction of the PAR (e.g., for the case of fluid-roof claddings) must be addressed. In addition, for systems with solar concentrators which are installed in the roof of the greenhouse, factors such as the durability in adverse weather conditions, wind durability, aesthetics, cost, architectural integrability, feasibility from practical point of view, must be taken into consideration. Furthermore, the NIR-filtering movable screens should be used for shading outside the greenhouse cover in order not to affect the ventilation of the greenhouse.

Another category is the UV-blocking materials. The studies available in the literature reveal that these claddings are of great interest since they are related with plants growth, detrimental and pollinator insects as well as with fungus sporulation and rose petal blackening. The results of relevant studies show that growing soilless eggplant under UV-absorbing material can be achieved with the same or better results as under standard covering material. Increase of red-leaf lettuce pigmentation with increasing UV was also observed. Furthermore, UV-blocking covers decrease the spread of virus and reduce the activity of detrimental insects such as whiteflies, providing an interesting option for Integrated Pest Management (IPM) without use of chemicals. In addition, UV-b followed by low leaf temperatures results in petal blackening of red rose cultivars (dark coloration on the outer petals), causing considerable financial losses to the growers. On the other hand, coverings which transmit more UV light may result in less bee losses, thus growers must balance various factors when considering which kind of covering to install. Growers using UV-blocking claddings could reduce bee losses by using fan ventilation systems or screened gutter vents. In general, before using UV-blocking covers, a preliminary test is desirable especially for some cases such as: when bumblebees are used as pollinators; beneficial insects are utilized; purple plants are cultivated. At this point it should be mentioned that the humidity and the temperature of the air of greenhouse interior space are associated with diseases development, thus by using a specific cover such as a UV-blocking does not necessary means that disease control is effective.

Conclusively, the presented claddings show interest and can have several benefits provided: (1) they are used with a cost-effective way, (2) aspects such as their practical applicability and mechanical load are addressed, (3) their selection is climate- and plant-specific. On the other hand, in the frame of the promotion of environmental friendly technologies, solar energy systems such as FLs combined with simple CT or with CPV or CPVT can be

applied for cultivation of crops as well as for algae cultivation. The advantages of these systems include: light/temperature control, production of heat and electricity for greenhouse energy needs. Especially, the combination FL–CT seems to be a promising and cost-effective solution. Given the environmental concerns of the last years, the concept of "Renewable Energy Greenhouses" should be promoted.

References

[1] Chou MD, Lee KT. Parameterizations for the absorption of solar radiation by water vapor and ozone. American Meteorological Society 1996;53:1203–8.
[2] Frederick JE. Principles of atmospheric Science. LLC, US: Jones and Bartlett Publishers; 2008.
[3] ISO 20473:2007, Optics and Photonics—Spectral Bands, ISO, Geneva.
[4] Chemisana D, Lamnatou Chr, Tripanagnostopoulos Y. The effect of Fresnel lens—solar absorber systems in greenhouses. Acta Horticulturae 2012;952:425–32.
[5] Kurata K. Scale-model experiments of applying a Fresnel prism to greenhouse covering, Sol. Energy 1999;46:53–7.
[6] Mavrogianopoulos GN. Greenhouses. third ed. Athens: Ath. Stamoulis; 2001.
[7] Sonneveld PJ, Swinkels GLAM, Bot GPA, Flamand G. Feasibility study for combining cooling and high grade energy production in a solar greenhouse. Biosystems Engineering 2010;105:51–8.
[8] Sonneveld PJ, Swinkels GLAM, Campen J, Van Tuijl BAJ, Janssen HJJ, Bot GPA. Performance results of a solar greenhouse combining electrical and thermal energy production. Biosystems Engineering 2010;106:48–57.
[9] Lamnatou Chr, Chemisana D. Solar radiation manipulations and their role in greenhouse claddings: Fluorescent Solar Concentrators, Photoselective and other materials. Submitted to the 'Renewable & Sustainable Energy Reviews'; 2012. Current status: under review.
[10] Sharma AK, Wahab S, Srivastava R. Agriculture diversification: problems and perspectives. New Delhi: I.K. International Publishing House Pvt. Ltd; 2010.
[11] Kläring HP, Klopotek Y, Schmidt U, Tantau HJ. Screening a cucumber crop during leaf area development reduces yield. Annals of Applied Biology 2012;161:161–8.
[12] Paradiso R, Van Ieperen W, Hogewoning SW, Meinen E, Snel JFH, Marcelis LFM. Light use efficiency at different wavelengths in rose plants. Acta Horticulturae 2011;893:849–56.
[13] 〈http://hrt.msu.edu/Energy/Notebook/pdf/Sec1/AJ_Both_Greenhouse_Glazing.pdf〉.
[14] Chemisana D, Ibáñez M, Barrau J. Comparison of Fresnel concentrators for building integrated photovoltaics. Energy Conversion and Management 2009;50:1079–84.
[15] Chemisana D, Vossier A, Pujol L, Perona A, Mollet A. Characterization of Fresnel lens optical performances using an opal diffuser. Energy Conversion and Management 2011;52:658–63.
[16] Chemisana Villegas D. Building integration solutions for CPV. Advances in Science and Technology 2010;74:278–87.
[17] Chemisana D, Ibáñez M. Linear Fresnel concentrators for building integrated applications. Energy Conversion and Management 2010;51:1476–80.
[18] Chemisana D. Building integrated concentrating photovoltaics: a review. Renewable and Sustainable Energy Reviews 2011;15:603–11.
[19] Sonneveld PJ, Swinkels GLAM, van Tuijl BAJ, Janssen HJJ, Campen J, Bot GPA. Performance of a concentrated photovoltaic energy system with static linear Fresnel lenses. Solar Energy 2011;85(2011):432–42.
[20] Tripanagnostopoulos Y, Siabekou Ch, Tonui JK. The Fresnel lens concept for solar control of buildings. Solar Energy 2007;81:661–75.
[21] Kacira M, Sase S, Okushima L. Optimization of vent configuration by evaluating greenhouse and plant canopy ventilation rates under wind-induced ventilation. Trans ASABE 2004;47:2059–67.
[22] Bartzanas T, Boulard T, Kittas C. Effect of vent arrangement on windward ventilation of a tunnel greenhouse. Biosystems Engineering 2004;88:479–90.
[23] Lee IB, Hong SW, Hwang HS, Seo IH. Study on ventilation efficiencies of naturally ventilated multi-span greenhouses in Korea. Acta Horticulturae 2006;719:341–8.
[24] Suay R, Gutiérrez A, López S, Moltó E. Monitoring and mapping temperature and humidity in greenhouses. Acta Horticulturae 2008;801:979–86.
[25] Jirka V, Kuceravy V, Maly M, Pech F, Pokorny J. Energy flow in a greenhouse equipped with glass raster lenses. Renew Energy 1999;16:660–4.
[26] Sonneveld PJ, Swinkels GLAM, Van Tuijl BAJ, Janssen H, De Zwart HF. Up scaling and test results of an advanced Fresnel greenhouse. Acta Horticulturae 2012;952:531–8.
[27] Sonneveld P, Zahn H, Swinkels GJ, A CPV System with Static Linear Fresnel Lenses in a greenhouse, 6th International Conference on Concentrating Photovoltaic Systems ICPV-6, April 7–9, 2010c, Freiburg, Germany.
[28] Korecko J, Jirka V, Sourek B, Cerveny J. Module greenhouse with high efficiency of transformation of solar energy, utilizing active and passive glass optical rasters. Solar Energy 2010;84:1794–808.
[29] Chemisana D, Lamnatou Chr, Tripanagnostopoulos Y, Fresnel Solar Concentrators for Agriculture Applications, International Conference of Agricultural Engineering CIGR-AgEng2012, July 8–12, 2012b, Valencia, Spain.
[30] Masojídek J, Sergejevová M, Rottnerová K, Jirka V, Korečko J, Kopecký J, et al. A two-stage solar photobioreactor for cultivation of microalgae based on solar concentrators. Applied Phycology 2009;21:55–63.
[31] Sonneveld PJ, Swinkels GLAM, Kempkes F, Campen JB, Bot GPA. Greenhouse with an Integrated NIR Filter and a solar cooling system. Acta Horticulturae 2006;719:123–30.
[32] Sonneveld PJ, Holterman HJ, Swinkels GLAM, Van Tuijl BAJ, Bot GPA. Solar energy delivering greenhouse with an integrated NIR filter. Acta Horticulturae 2008;801:703–10.
[33] Sonneveld PJ, Swinkels GLAM, Bot GPA. Design of a solar greenhouse with energy delivery by the conversion of near infrared radiation—Part 1 optics and PV-cells. Acta Horticulturae 2009;807:47–53.
[34] López-Marín J, González A, García-Alonso Y, Espí E, Salmerón A, Fontecha A, et al. Use of cool plastic films for greenhouse covering in Southern Spain. Acta Horticulturae 2008;801:181–6.
[35] Kempkes FLK, Hemming S. Calculation of NIR effect on greenhouse climate in various conditions. Acta Horticulturae 2012;927:543–50.
[36] Hemming S, Kempkes F, Van der Braak N, Dueck T, Marissen N. Greenhouse Cooling by NIR-reflection. Acta Horticulturae 2006;719:97–105.
[37] Mutwiwa UN, Tantau HJ, Salokhe VM. Response of tomato plants to natural ventilation and evaporative cooling methods. Acta Horticulturae 2006;719:447–54.
[38] Daponte T. Recent advances in photoselective films with interference effects. Plant production in closed ecosystems. Dordrecht, NL: Kluwer Academic; 1997 123–138.
[39] Von Elsner B. Interference pigments in photoselective shading paint for greenhouses. Acta Horticulturae 2006;711:417–22.
[40] Blanchard MG, Runkle ES. Influence of NIR-reflecting shading paint on greenhouse environment, plant temperature, and growth and flowering of bedding plants. Transactions of the ASABE 2010;53:939–44.
[41] Verlodt I, Verschaeren P, New P. interference film for climate control. Acta Horticulturae 1998;514:139–46.
[42] García-Alonso Y, González A, López J, Espí E, Salmerón A, Fontecha A. New cool plastic films for greenhouse covering in tropical and subtropical areas. Acta Horticulturae 2006;719:131–7.
[43] Hemming S, Kempkes F, Van der Braak N, Dueck T, Marissen N. Filtering natural light at the greenhouse covering—better greenhouse climate and higher production by filtering out NIR? Acta Horticulturae 2005;711: 411–6.
[44] Kempkes F, Stanghellini C, Hemming S, Dai J. Cover materials excluding near infrared radiation: effect on greenhouse climate and plant processes. Acta Horticulturae 2008;797:477–82.
[45] Hemming S, Waaijenberg D, Campen JB, Bot GPA. Impron I, Development of a greenhouse system for tropical lowland in Indonesia. Acta Horticulturae 2006;710:135–42.
[46] Feuermann D, Kopel R, Zeroni M, Levi S, Gale J. Evaluation of a liquid radiation filter greenhouse in a desert environment. Trans ASAE 1998;41:1781–8.
[47] Feuermann D, Kopel R, Zeroni M, Levi S, Gale J. Theory and validation of a liquid radiation filter greenhouse simulation for performance prediction. Trans ASAE 1997;40:175–84.
[48] Gale J, Feuermann D, Sivan D, Kopel R, Shlomo E. Engineering and economics of liquid radiation filter greenhouses. Acta Horticulturae 2000;534: 361–6.
[49] Abdel-Ghany AM, Al-Helal IM, Alzahrani SM, Alsadon AA, Ali IM, Elleithy RM. Covering materials incorporating radiation-preventing techniques to meet greenhouse cooling challenges in arid regions: a review. ScientificWorldJournal 2012.
[50] Raviv M, Antignus Y. UV radiation effects on pathogens and insect pests of greenhouse-grown crops. Photochemistry and Photobiology 2004;79: 219–26.
[51] Díaz BM, Biurrún R, Moreno A, Nebreda M, Fereres A. Impact of Ultraviolet-blocking plastic films on insect vectors of virus diseases infesting crisp lettuce. HortScience 2006;41:711–6.
[52] Kittas C, Papaioannou Ch, Obeid D, Katsoulas N, Tchamitchian M. Effect of two UV-absorbing greenhouse-covering films on growth and yield of an eggplant soilless crop. Scientia Horticulturae 2006;110:30–7.
[53] C Kittas, Ch Papaioanou, D Obeid, N Katsoulas, M Tchamitchian, Effect of two new UV-absorbing greenhouse-covering films on growth and yield of a tomato soilless crop, International Symposium of thee CIGR in New trends in Farm buildings, May 2–6, 2004, Evora, Portugal.
[54] Krizek DT, Britz SJ, Mirecki RM. Inhibitory effects of ambient levels of solar UV-A and UV-B radiation on growth of cv. New Red Fire letuce Physiol Plant 1998;103:1–7.
[55] Garcia-Macias P, Ordidge M, Vysini E, Waroonphan S, Battey NH, Gordon MH, et al. Changes in the Flavonoid and Phenolic acid contents and antioxidant activity of red leaf lettuce (Lollo Rosso) due to cultivation under plastic films varying in ultraviolet transparency. Journal of Agricultural and Food Chemistry 2007;55:10168–72.
[56] Oh MM, Carey EE, Rajashekar CB. Antioxidant phytochemicals in lettuce grown in high tunnels and open field. Horticulture, Environment, and Biotechnology 2011;52:133–9.
[57] Paul ND, Jacobson RJ, Taylor A, Wargent JJ, Moore JP. The use of wavelength selective plastic cladding materials in horticulture: understanding of crop and fungal responses through the assessment of biological spectral weighting functions. Photochemistry and Photobiology 2005;81:1052–60.

[58] Kishima Y, Shimaya A, Adachi T. Evidence that blue light induces betalain pigmentation in Portulaca callus. Plant Cell, Tissue and Organ Culture 1995;43:67–70.

[59] Wargent JJ, Taylor A, Paul ND. UV supplementation for growth regulation and disease control. Acta Horticulturae 2006;711:333–8.

[60] Reuveni R, Raviv M. Control of downy mildew in greenhouse-grown cucumbers using blue photoselective polyethylene sheet. Plant Disease 1997;81:999–1004.

[61] Chen P, Liu T, Wang D, Zhang O, Hu L. Modified vinyl-POSS materials as sun protection factor and as films for greenhouse cover. Ferroelectrics 2011;411:36–43.

[62] Wang D, Wei S, Hu L. POSS/TiO_2 nanohybrids as sun protection ingredients for greenhouse covers. Advanced Materials Research 2010;113–116:2077–80.

[63] Antignus Y. Manipulation of wavelength-dependent behaviour of insects: an IPM tool to impede insects and restrict epidemics of insect-borne viruses. Virus Research 2000;71:213–20.

[64] Diaz BM, Fereres A. Ultraviolet-blocking materials as a physical barrier to control insect pests and plant pathogens in protected crops. Pest Technology 2007;1:85–95.

[65] Legarrea S, Betancourt M, Plaza M, Fraile A, García-Arenal F, Fereres A. Dynamics of nonpersistent aphid-borne viruses in lettuce crops covered with UV-absorbing nets. Virus Research 2012;165:1–8.

[66] Chyzik R, Dobrinin S, Antignus Y. Effect of a UV-deficient environment on the biology and flight activity of Myzus persicae and its hymenopterous parasite Aphidius matricariae. Phytoparasitica 2003;31:467–77.

[67] Antignus Y, Nestel D, Cohen S, Lapidot M, Ultraviolet-deficient M. Greenhouse environment affects whitefly attraction and flight-behavior. Entomological Society of America 2001;30:394–9.

[68] Mutwiwa UN, Borgemeister C, Von elsner B, Tantau H-J. Effects of UV-absorbing plastic films on greenhouse whitefly (Homoptera: Aleyrodidae). Journal of Economic Entomology 2005;98:1221–8.

[69] López-Marin J, Rodríguez M, González A. Effect of ultraviolet-blocking plastic films on insect vectors of virus diseases infesting tomato (Lycopersicon esculentum) in greenhouse. Acta Horticulturae 2011;914:175–9.

[70] Doukas D, Payne CC. The use of ultraviolet-blocking films in insect pest management in the UK; effects on naturally occurring arthropod pest and natural enemy populations in a protected cucumber crop. Annals of Applied Biology 2007;151:221–31.

[71] Nishizawa T, Shishido Y, Sasaki B, Sato C, Hanawa Y, Matsumura K. Effects of specific UV-blocking on plant growth and insect control. Acta Horticulturae 2012;927:203–10.

[72] Kigathi R, Poehling H-M. UV-absorbing films and nets affect the dispersal of western flower thrips, Frankliniella occidentalis (Thysanoptera: Thripidae). Journal of Applied Entomology 2012.

[73] Vatsanidou A, Bartzanas T, Papaioannou C, Kittas C. Efficiency of physical means of IPM on insect population control in greenhouse crops. Acta Horticulturae 2011;893:1247–54.

[74] Chiel E, Messika Y, Steinberg S, Antignus Y. The effect of UV-absorbing plastic sheet on the attraction and host location ability of three parasitoids: aphidius colemani, Diglyphus isaea and Eretmocerus mundus. BioControl 2006;51:65–78.

[75] Krizek DT, Clark HD, Mirecki RM. Spectral properties of selected UV-blocking and UV-transmitting covering materials with application for production of high-value crops in high tunnels. Photochemistry and Photobiology 2005;81:1047–51.

[76] González A, García-Alonso Y, Espí E, Fontecha A, Salmerón A. Viral diseases control with UV-blocking films in greenhouses of Southern Spain. Acta Horticulturae 2004;659:331–8.

[77] Dyer AG, Chittka L. Bumblebee search time without ultraviolet light. The Journal of Experimental Biology 2004;207:1683–8.

[78] Morandin LA, Laverty TM, Kevan PG, Khosla S, Shipp L. Bumble bee (Hymenoptera: Apidae) activity and loss in commercial tomato greenhouses. The Canadian Entomologist 2001;133:883–93.

[79] Morandin LA, Laverty TM, Gegear RJ. Effect of greenhouse polyethelene covering on activity level and photo-response of bumble bees. The Canadian Entomologist 2002;134:539–49.

[80] Hausbeck MK, Moorman GM. Managing *Botrytis* in greenhouse-grown flower crops. Plant Disease 1996;80:1212–9.

[81] Honda Y. Control of seedling blast of rice with ultraviolet-absorbing vinyl film. Plant Disease 1985;69.

[82] Nicot PC, Mermier M, Vaissiere BE. Differential spore production by *Botrytis* cinerae on Agar medium and plant tissue under near-ultraviolet light-absorbing polyethylene film. Plant Disease 1996;80:555–8.

[83] Sasaki T, Honda Y. Control of certain diseases of greenhouse vegetables with ultraviolet-absorbing vinyl film. Plant Disease 1985;69:530–3.

[84] Reuveni R, Raviv M, Bar R. Sporulation of *Botrytis* cinerea as affected by photoselective polyethylene sheets and filters. Annals of Applied Biology 1989;115:417–24.

[85] Tan KK. Blue-light inhibition of sporulation in *Botrytis* cinerea. Journal of General Microbiology 1974;82:201–2.

[86] Elad Y. Effect of filtration of solar light on the production of conidia by field isolates of *Botrytis* cinerea and on several diseases of greenhouse-grown vegetables. Crop Protection 1997;16:635–42.

[87] Paul ND, Jacobson RJ, Taylor A, Wargent JJ, Moore JP. The use of wavelength selective plastic cladding materials in horticulture: understanding of crop and fungal responses through the assessment of biological spectral weighting functions. Photochemistry and Photobiology 2005;81:1052–60.

[88] Raviv M. The use of photoselective cladding materials as modifiers of morphogenesis of plants and pathogens. Acta Horticulturae 1989;246:275–84.

[89] Aguyoh JN, Gaoquiong L, Ochieng J. Influence of greenhouse cover material on light transmission, aphids, mites, powdery mildew and rose petal colour. Agriculture in the Tropics and Subtropics 2010;43:232–5.